Design of a Monocular Multi-Spectral Skin Detection,
Melanin Estimation, and False-Alarm Suppression System

THESIS

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AFIT/GE/ENG/10-24

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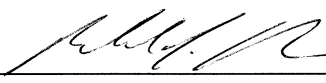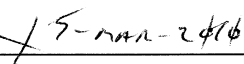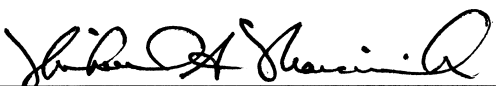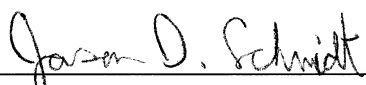
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DESIGN OF A MONOCULAR MULTI-SPECTRAL SKIN DETECTION, MELANIN ESTIMATION, AND FALSE-ALARM SUPPRESSION SYSTEM

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Abstract

A real-time skin detection, false-alarm reduction, and melanin estimation system is designed targeting search and rescue (SAR) with application to special operations for manhunting and human measurement and signatures intelligence. A mathematical model of the system is developed and used to determine how the physical system performs under illumination, target-to-sensor distance, and target-type scenarios. This aspect is important to the SAR community to gain an understanding of the deployability in different operating environments. A multi-spectral approach is developed and consists of two short-wave infrared cameras and two visible cameras. Through an optical chain of lenses, custom designed and fabricated dichroic mirrors, and filters, each camera receives the correct spectral information to perform skin detection, melanin estimation, and false-alarm suppression. To get accurate skin detections under several illumination conditions, the signal processing is accomplished in reflectance space, which is estimated from known reflectance objects in the scene. Model-generated output of imaged skin, when converted to estimated reflectance, indicates a good correspondence with skin reflectance. Furthermore, measured and modeled estimates of skin reflectance indicate a good correspondence with skin reflectance.

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Design of a Monocular Multi-Spectral Skin Detection, Melanin Estimation, and False-Alarm Suppression System

I. Introduction

Hyper and multi-spectral imaging is used in a wide range of scientific disciplines. Recently, there has been a push towards the use of hyper-spectral imaging for search and rescue missions. An example of this is the Civil Air Patrol's Airborne Real-Time Cueing Hyperspectral Enhanced Reconnaissance (ARCHER), which uses hyperspectral data from 500-1100nm to help in Search and Rescue (SAR) missions [27]. For use in the SAR application, hyper-spectral imagery requires high spatial and spectral resolution. To meet these requirements, line scanning imagers must have a small field of view (FOV) and scan quickly. The HyperSpecTIR 3 (HST3) line scanning hyper-spectral camera used by the Sensors Exploitation Research Group takes about 10 seconds to scan an image, which is typical of line scanning instruments. The slow acquisition makes the capture of motion, or use for real-time detection, infeasible. Following the work by Nunez [23], a real-time multi-spectral detection system is developed.

The system developed in this thesis exploits the reflectance of human skin in the near-infrared (NIR) to help identify it as a unique material of interest. The concept has been proven to work with a hyper-spectral imager, and is mature enough to be transformed into a compact monocular multi-spectral detection system. The skin detection, false-alarm suppression, and melanin estimation system under development uses the visible spectrum and three other specific wavelength bands, divided over four cameras. Bands around 1080 and 1580nm are used for skin detection, while bands around 800 and 1080nm are used for melanin estimation. The visible spectrum is used for false-alarm suppression as well as a high-resolution color image of the scene. A single fore optic is used to minimize registration problems, making the pixel-by-

pixel comparison faster and more accurate than a system with four separate objective lenses.

A multi-spectral detection system of the type developed here has several potential uses. Search and Rescue is a demanding task that requires large teams of people doing what is frequently a blind search. These searches can take more time than the victim has to wait. Airborne searches rely on the talent, and in some cases luck, of analysts and the imagery on hand. Although this does not seem to be a complete solution, it should be able to take most of the guesswork out of the analysts' job. This is accomplished by providing a cueing mechanism, so the analysts can focus their image collection and analysis efforts on the areas identified as having skin. Furthermore, ground crews can be more efficiently tasked to those areas of interest. This system further has an advantage over thermal detection, since it can detect the skin of living or dead subjects. Special/covert operations may find this system useful, as the wavelengths used for skin detection and melanin estimation are beyond the visible light spectrum. With near-infrared illumination, skin detection can be accomplished in low light conditions, or even in the dark. Melanin estimation can make the searches for missing people, or finding criminals on the run, much easier. The system designed will moreover be used by other researchers to find ways to use specific human motion and emotion to classify actions that could be a concern.

1.1 *Problem Statement*

A multi-spectral skin detection, melanin estimation, and false-alarm reduction system is needed for the SAR problem. It must be able to image at a resolution of no more than 2-inch pixels from a slant range of $\sim$710 feet. Based on the following argument, 2×2 inch pixels were chosen to ensure that a few "pure skin pixels" of skin are imaged. A rough measurement of a typical adult hand and head were made and the results are shown in Table 1.1. The imaging scenario assumes that the camera, hand, and head are aligned such that their major axis is aligned with the vertical direction of the camera. The squares in Figures 1.1 and 1.2 represent the two inch

Table 1.1:   Model shape and size of hand and head used in determining required pixel sizes. Values are determined by measuring the hand and head of a typical adult male.

Body Part	Modeled Shape	Modeled Size (in)
Head	Ellipse	8×6
Neck	Rectangle	3.5×5
Hand minus fingertips	Rectangle	6×3.5
Fingertips	Rectangle	1×1.75
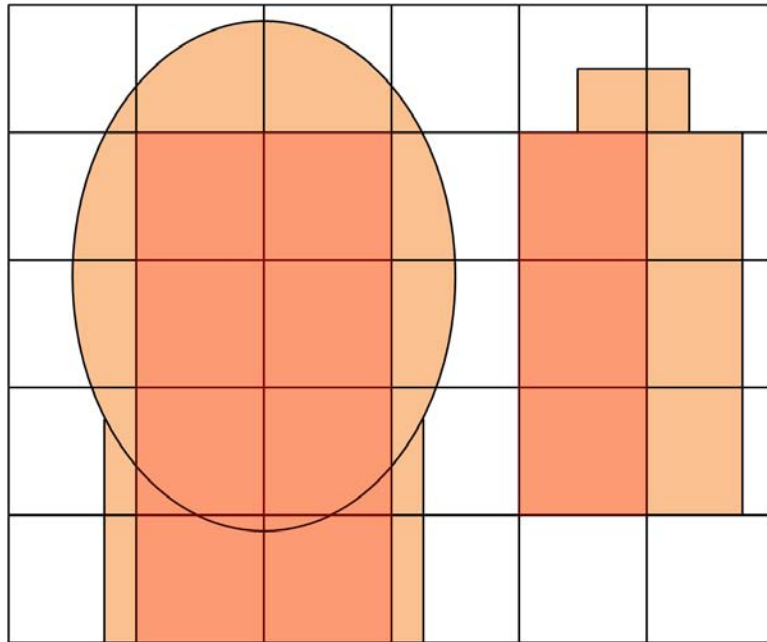
Figure 1.1:   To scale 2in pixels corresponding to the measured head and hand size. This shows the best case scenario with pure skin pixels shown in red.

imaged pixels and are to scale with the modeled head and hand. The "pure skin pixels" are colored in red so they can be easily seen. The best case scenario (Fig. 1.1), using 2×2 inch pixels has 8 pixels on the head and 3 on the hand. The worst case scenario (Fig. 1.2) gives 3 on the head and 0 on the hand. Even in the worst case scenario, there are at least 2 "pure skin pixels" of skin for the system to detect.

This imaging distance is based on the assumption that the search aircraft flies at 500ft above ground level with a camera looking out at 45° and off to the side at 30°, as
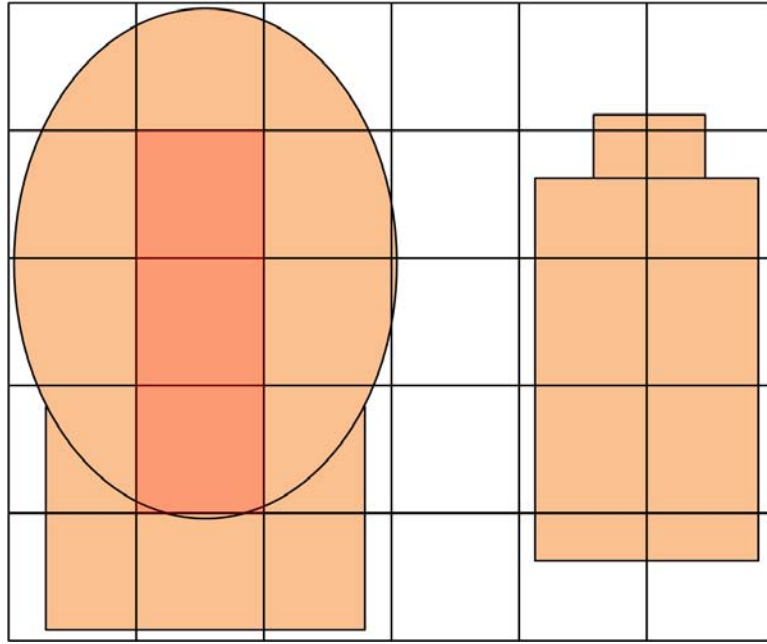
Figure 1.2:   To scale 2in pixels corresponding to the measured head and hand size. This shows the worst case scenario with the pure skin pixels shown in red.

shown in Fig. 1.3[1]. This system needs to acquire imagery and process it at a baseline 1fps. The cameras chosen are capable of higher frame rates, so as the detection algorithms become faster, higher frame rates will be physically available. A single fore optic is used to reduce registration problems inherent in multi-lens systems. The system is additionally designed to remain a passive detection system, even in low-light conditions. A model of this system is made to fine tune the detection thresholds.

To accomplish the stated requirements, six essential pieces must be considered: fore optic, secondary lens (to account for the pixel size differences), iris diaphragms, dichroic mirrors to efficiently segment the light energy, filters to focus on necessary features, and cameras to perform the imaging. A block diagram of the system is shown in Fig. 1.4.

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[1]Private communications with Mr. Chris Rowley, President and Director of Operations, Volunteer Imaging Analysts for Search and Rescue, March 2009,(http://www.viasar.org) [25]
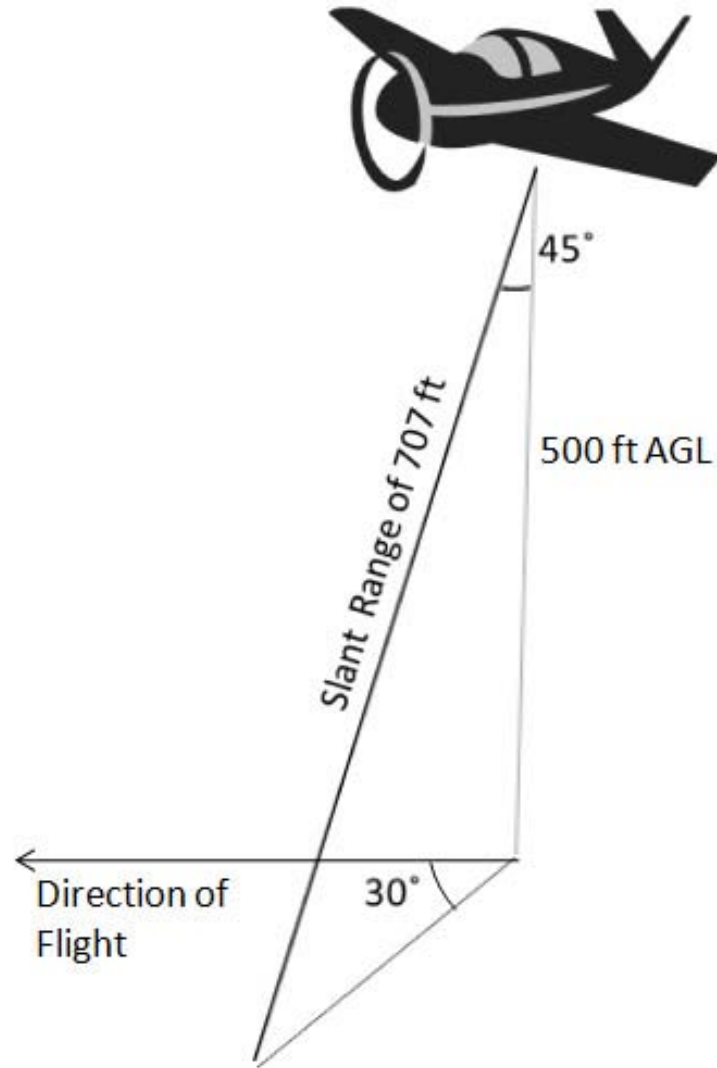
Figure 1.3: Data acquisition scenario for search and rescue where the search aircraft flies at approximately 500 ft above ground level and camera system is aimed at an approximate 45° depression angle and 30° off angle.

1.2 Background and Related Research

The work in human skin detection that formed the basis for this thesis was accomplished at the Air Force Institute of Technology in [23]. The author in [23] created a diffuse model of human skin by examining its optical properties. From this model, several scenarios were studied and efficient algorithms for skin detection, false-alarm suppression, and melanin estimation were specified. The first attempt at performing skin detection with sensors was with the HyperSpecTIR 3 (HST3). This is
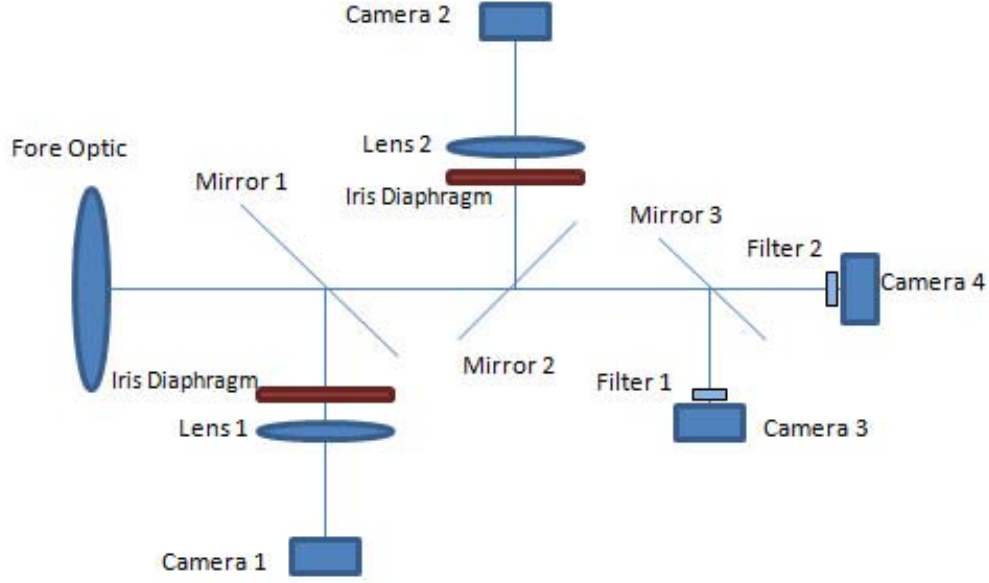
Figure 1.4:   Block diagram for the monocular skin detection, melanin estimation, and false-alarm suppression camera system developed in this thesis.

a hyperspectral imager designed by SpecTIR [16], originally for airborne applications. The HST3 is a line scanning imager that uses scanning mirrors and a prism to divide light into several hundred bands. The HST3 collects data in the range of 400-2500nm. The spectral bands are sampled nominally at 11nm in the VIS and 8nm in the NIR. The full width half maximum (FWHM) of each of the bands is approximately 14nm and 8nm in the visible and NIR respectively.

Due to their often large nature and typical slow scan times, line scanning instruments such as the HST3 are not necessarily the best option for use on small aircraft or doing real-time detection. As stated above, it was the right type of imager for doing preliminary work and demonstrating the potential on real images. An example of the general capability of skin detection, false-alarm suppression, and melanin estimation is shown in Fig. 1.5 where the are images taken with the HST3.

Since general wavelength bands were found from the theoretical modeling work in conjunction with images from the HST3, a solution could be found that would allow one to achieve real-time detection in the NIR. The initial concept work used a stereo optic system using two Goodrich SUI640KTSX-1.7RT high sensitivity InGaAs

Figure 1.5:   (Top) RGB image of a test scene acquired with the HST3. (Bottom) Skin detection performed on the above image, where the image is colored based on melanin estimation [23].

NIR cameras, each with their own lens and filter, as shown in Fig. 1.6. (The cameras are discussed in more detail in Section 3.1.) Figure 1.7 shows an image from each camera and the resulting skin detection. The false detections seen are due to low power in the images or shadows.

The stereo optic approach has an inherent registration problem due to having separate lenses. If such a system is fielded, it would require four cameras, each with its own set of optics, which complicates the registration problem caused by different objects at different distances in the scene. Figure 1.8 shows a close-up picture of the stereo optic system performing skin detection, where the "target" is holding the detection system display. The skin detection performs well but there are false detections mostly at edges from objects occurring at different distances from the camera. Another factor is the cost of buying four sets of optics, one for each
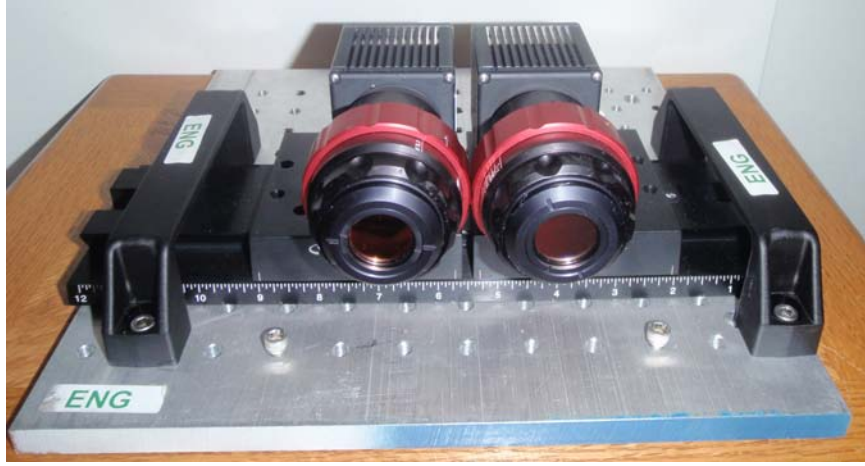
Figure 1.6:   Snapshot of the prototype two-band, real-time skin detection system.

camera. The single optic design proposed in Fig. 1.4, removes the need for continuous registration and several fore optic lenses.

The filters used on the two camera system were measured by a Casey spectrophotometer 5000 to determine their transmission properties. These filters are ThorLabs 25.4mm bandpass filters, which are specified as having center wavelengths of 1050 and 1550 and bandwidths of 10nm and 12nm respectively. Figure 1.9 shows the transmission measured for each. Using these filters, the stereo optic system is receives at most 60% of the incident light to the focal plane array. Furthermore, we see that the 1050nm center wavelengths is off by 3nm. A carefully designed optical system will improve on the relatively poor performance exhibited by the prototype system.

1.3   Thesis Overview

Chapter II provides an introduction to radiometry and how it is used to determine the spectral energy incident on the fore optic of the system and how many electron forming photons will strike the focal plane array. The basics of skin detection, false-alarm reduction, and melanin estimation are discussed. This includes justification of specific wavelengths chosen as well as the algorithms used to perform the detection. Additionally, specifics of the features subsequently used in detection, false-alarm suppression, and melanin estimation are covered. Finally an overview of

Figure 1.7: (Top) Image seen through the 1080nm filter. (Middle) Image seen through the 1550nm filter. (Bottom) Skin detection resulting from the skin detection methodology applied to the top and middle images.

geometric optics is covered. Chapter III introduces the criteria from which the system components are chosen, as well as the development of an optical model for the

Figure 1.8:   Close in view of skin detection shown using the camera system in Fig. 1.6. The false detections due to distance-dependent registration problems [23].

detection system. Chapter IV gives a comparison of the model results to real images acquired with the developed system. Finally, Chapter V provides a summary of what is done, the results, future work, and the contribution this thesis work has on SAR and H-MASINT work.
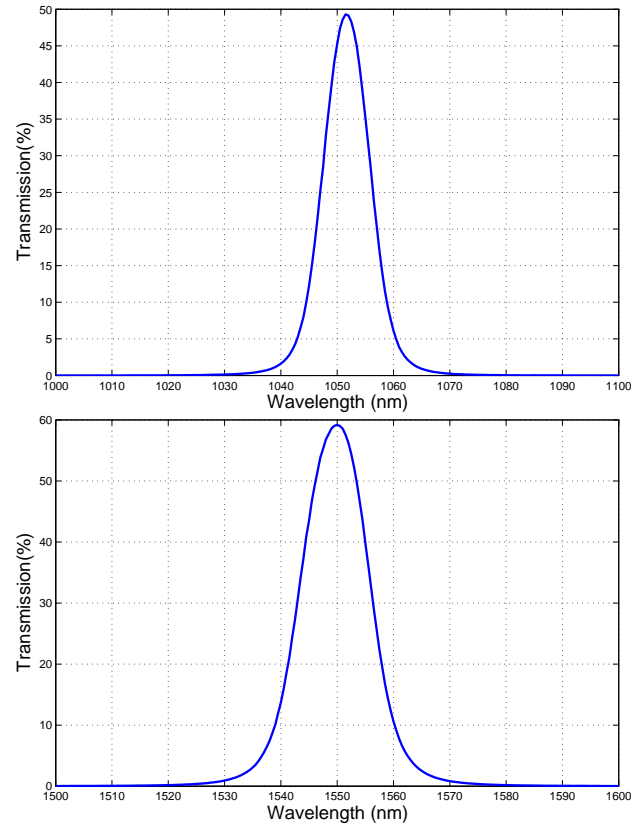
Figure 1.9: (Top) Transmission of the ThorLabs 1050nm center wavelength, 10nm bandwidth bandpass filter. (Note the filter's measured center wavelength is approximately 1053nm.) (Bottom) Transmission of the Thor-Labs 1550nm center wavelength, 12nm bandwidth bandpass filter. Both band pass filters were measured by a Casey spectrophotometer 5000.

II. Background

This chapter covers the background necessary to understand the features exploited and methods used for skin detection which are necessary to build the system. The reflectance properties of human skin are discussed to give the reader a basis of why certain wavelengths were chosen. The algorithms used to perform the detections are discussed to show how the images are processed. Third, an overview of the geometric optics used to solve for lens focal lengths and diameters is completed. Lastly, a radiometry overview is accomplished to discuss how the model is created for this thesis.

2.1 Reflectance Properties of Human Skin

The wavelengths for skin detection, melanin estimation, and false-alarm suppression are specified in the existing literature [23, 24]. The reflectance of several types of skin are shown in Fig. 2.1 (Top). The skin reflectance shown was measured with a spectrometer. There are several properties of skin that create the features seen in the curves; including the indices of refraction of the air/skin interface, the absorption coefficient spectra of the constituent components of skin (water, collagen, melanin, hemoglobin, and others) and skin's scattering coefficient [23].

Water has the largest absorption affect in skin as it is skin's majority component [23]. Water absorption does not have a significant effect in the visible portion of the spectra (VIS), but there are important features in the near-infrared portion of the spectrum (NIR). Figure 2.2 shows the absorption coefficient of skin. The general trend of melanin absorption is shown in Fig. 2.3. Fig. 2.1 (Top) demonstrates how different levels of melanin in skin change its reflectance. The more melanin skin has, the more visible light it absorbs. Beyond 1100nm, melanosome absorption does not significantly affect skin reflectance, due to the absorption from water. The Fitzpatrick scale is used to describe skin color and its sensitivity to ultraviolet radiation, and is shown in Table 2.1 [21]. The color and the skin sensitivity to ultraviolet light directly relate to the percentage of epidermis volume occupied by melanosomes, shown in Ta-

Table 2.1:   Fitzpatrick scale used for describing skin color and sensitivity to ultra
              violet light. These correspond to the skin types shown in Fig. 2.1.

Skin Type	Skin Color	Sun Response
I	Very Fair	Always Burns
II	Fair	Usually Burns
III	White to Olive	Sometimes Burns
IV	Brown	Rarely Burns
V	Dark Brown	Very Rarely Burns
VI	Black	Never Burns

Table 2.2:   Percentage of epidermis volume occupied by melanosomes with respect
              to skin color.

Skin Color	Melanosome Content(%)
Light Skinned Adult	1.6-6.3
Moderately Pigmented Adult	11-16
Darkly Pigmented Adult	18-43

ble 2.2 [15]. Hemoglobin additionally has some absorption features that can be seen
in the reflectance curve. There are two types hemoglobin in the blood, oxygenated
and deoxygenated. Oxygenated and deoxygenated hemoglobin make up 75% and 25%
of the blood respectively [23]. The absorption of both types of hemoglobin drop off
as wavelength increases and once in the NIR, its effect is minimal. Figure 2.4 shows
the absorption of both oxygenated and deoxygenated hemoglobin out to 800nm. The
important features to note are the m-shaped absorption at $\sim 560nm$ and a local mini-
mum at $\sim 510nm$. Note that for deoxygenated hemoglobin, the m-shaped absorption
feature does not exist. There is, however, a local minimum at $\sim 480nm$ and a local
maximum at $\sim 560nm$. As shown in Fig. 2.1 as the amount of melanin increases, the
m-shaped feature begins to disappear.

2.2   Atmospheric Considerations

The atmosphere plays an important role in the decision as to what wavelengths
are chosen for the detections as well as how the detections are accomplished. Target
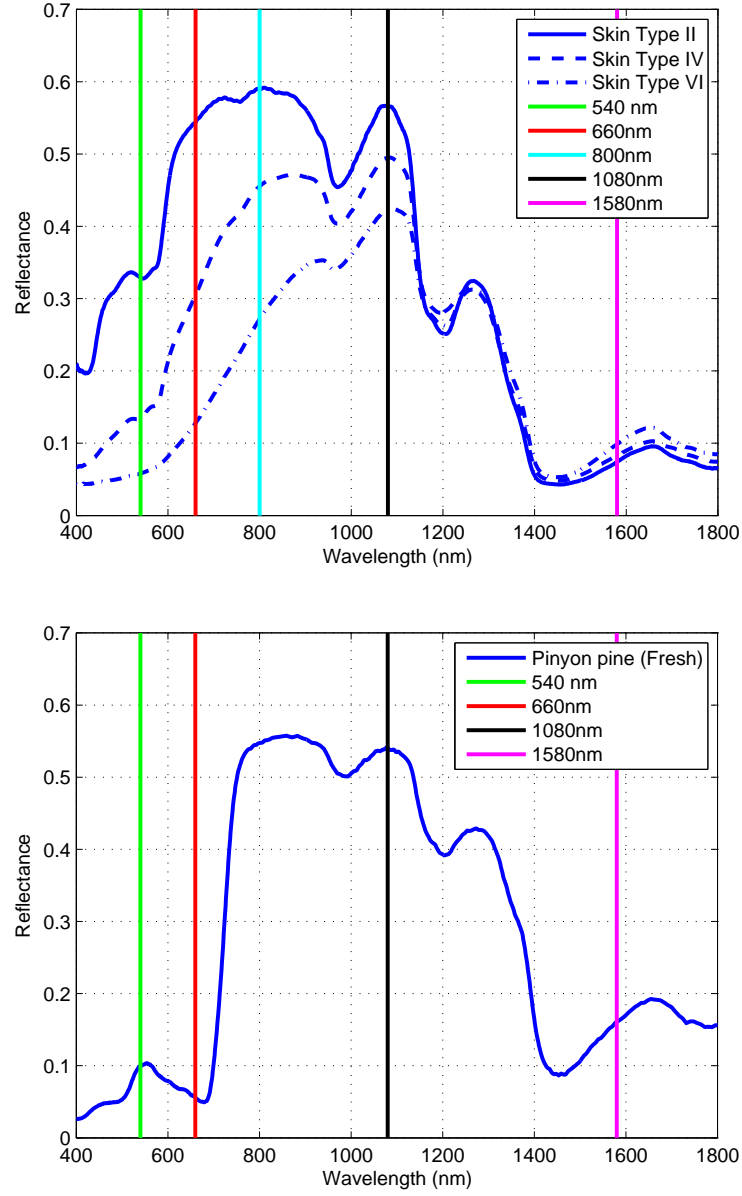
Figure 2.1:   (Top) Skin reflectance at several different melanin levels as described in
                Table 2.1 [24]. (Bottom) Reflectance of fresh Pinyon pine needles used
                to compare against skin above [5].

illuminations effect on the wavelengths chosen for skin detection, melanin estimation,

and false-alarm suppression is discussed.
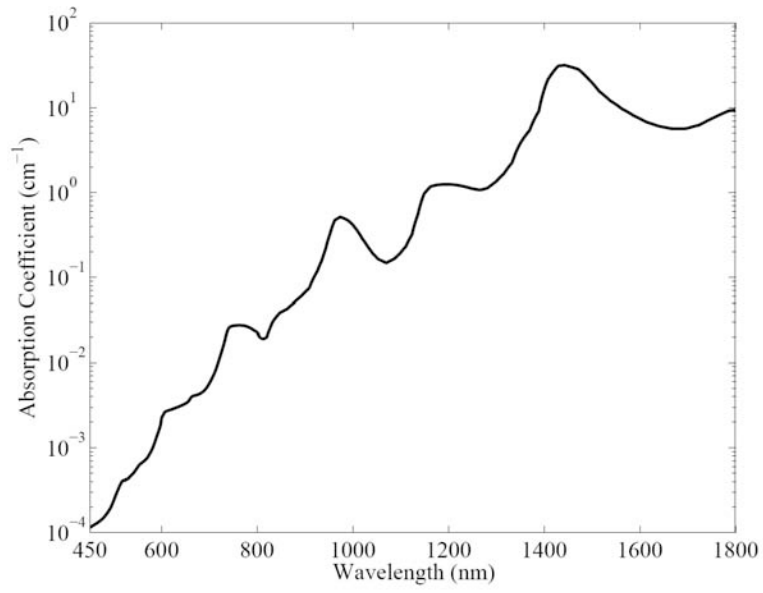
Figure 2.2:   Water absorption coefficient as a function of wavelength [23].
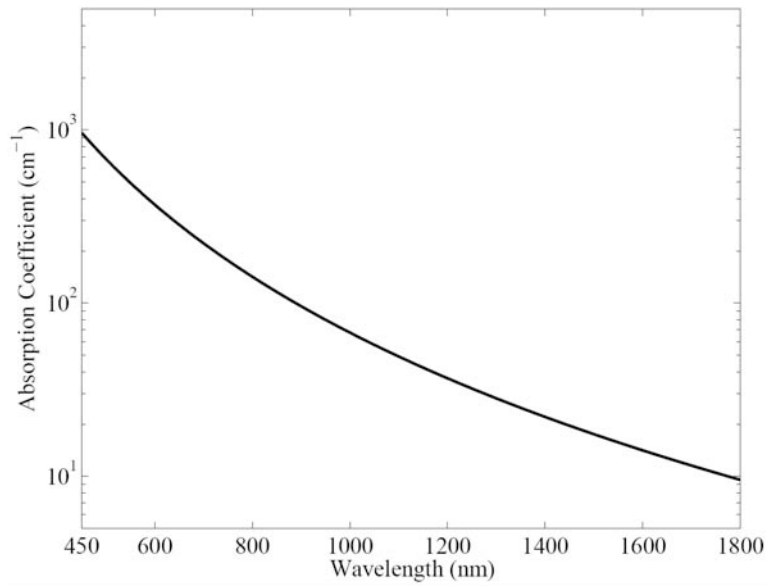
Figure 2.3:   Melanin absorption coefficient as a function of wavelength [23].

2.2.1   Solar Illumination.   Another important aspect to choosing the wavelengths for skin detection is the illumination source. Figure 2.5 shows typical spectral illumination for Dayton, OH on a sunny day.
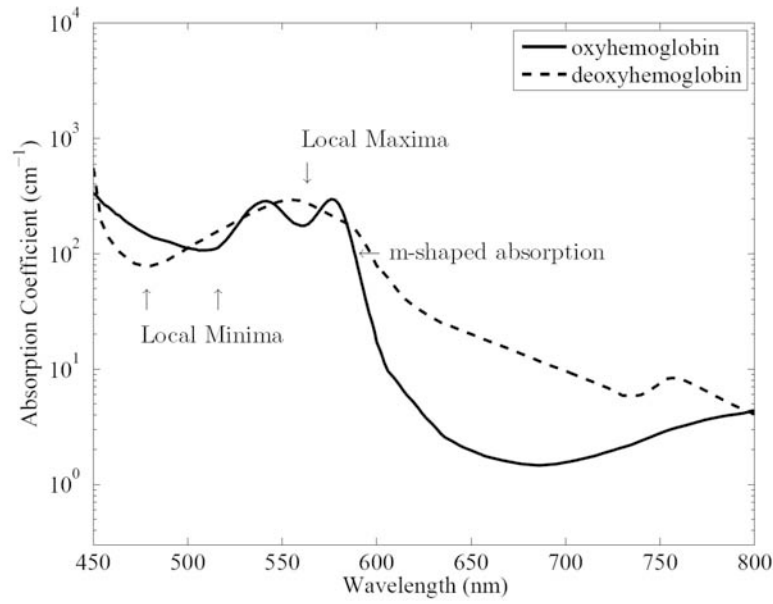
Figure 2.4:   This figure shows the measured oxygenated and deoxygenated hemoglobin absorption of skin [23].
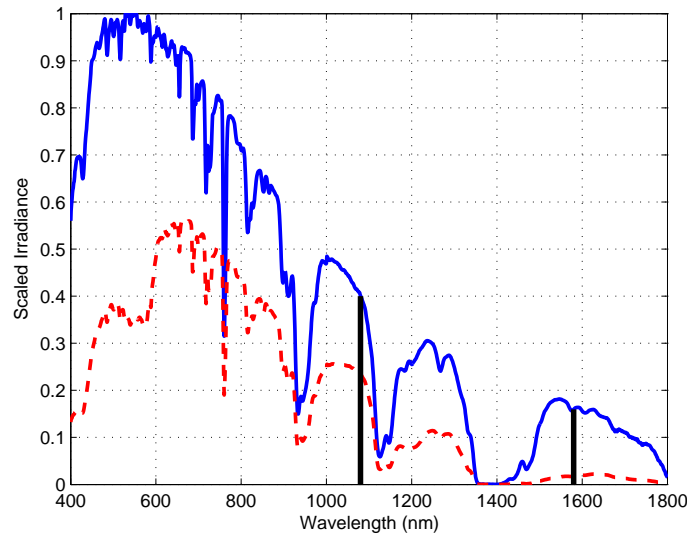
Figure 2.5:   (Solid) Solar irradiance in Dayton, OH on a sunny day scaled by the maximum irradiance. (Dashed) The radiance spectra of Type I/II skin illuminated by sunlight scaled by the same maximum irradiance. The vertical lines show where 1080 and 1580nm are located.

The irradiance is measured using a cosine receptor with a field spectrometer and is scaled so its maximum value is one. The dashed line shows irradiance multiplied

by model generated Type I/II skin reflectance from [23]. The important features to note are the atmospheric absorption bands. In a difference-based detection algorithm, the wavelengths with the largest difference in energy are top candidates. However, atmospheric water absorption bands, like those at 1400nm do not have enough energy to be imaged. As a result, when choosing wavelengths for this detection purpose, having enough energy to produce a high quality image is important. As such, 1080nm and 1580nm are used as specified in [23].

   2.2.2 Reflectance Estimation.   Many applications in hyperspectral remote sensing use images converted from radiance to reflectance. Reflectance is used because, unlike radiance, reflectance is a property of the material and independent of illumination. It is impossible to directly image a scene in reflectance using passive sensors. Passive imagery is typically in radiance, which is illumination-dependent. It is possible to transform an image from radiance to estimated-reflectance using one of several techniques. The technique used for the skin detection system, developed in this thesis, is the Empirical Line Method (ELM) [8]. To perform ELM, the reflectance and radiance measurement for at least one material in the scene must be known. The radiance measurement is taken from the values assigned to the image pixels and the known reflectance spectra from using a field spectrometer. The unknown reflectance parameters can be estimated by the affine transform specified as:

$$\hat{\rho}(\lambda) = \frac{L(\lambda) - \hat{b}(\lambda)}{\hat{a}(\lambda)} \tag{2.1}$$

where

$$\hat{a}(\lambda) = \frac{L_2(\lambda) - L_1(\lambda)}{\rho_2(\lambda) - \rho_1(\lambda)} \quad \text{and} \tag{2.2}$$

$$\hat{b}(\lambda) = \frac{L_1(\lambda)\rho_2(\lambda) - L_2(\lambda)\rho_1(\lambda)}{\rho_2(\lambda) - \rho_1(\lambda)} \quad . \tag{2.3}$$

In Eqns. (2.1) - (2.3), L_1, L_2 are the measured radiances that correspond to the known reflectance ρ_1, ρ_2 and (L) is the radiance of the pixel one is converting to reflectance. There are two important assumptions made when using this method. First, the scene that is being estimated is illuminated uniformly. Second, no pixel in the scene is saturated. If either of these are violated, then the linear relationship does not hold. In reality, the atmospheric effects are not linear, but they are approximated as linear by the remote sensing community.

An important detail to note regarding estimated reflectance is that the radiance values measured in the scene are a result of bi-directional reflectance. This is significant because the amount of light the camera receives depends on the angles of the illumination source and detector with respect to the target. These differences in illumination correspond to changes in the estimated reflectance. The bi-directional reflection of human skin is studied in [18, 20, 22, 31] and incorporating these effects is the goal of future modeling efforts.

2.3   Algorithms/Definitions

This section provides details of the computations required for the output of the optical system designed in this thesis. To this end, details of the skin detection, false-alarm suppression, and melanin estimation algorithms are provided.

2.3.1   Normalized Difference.   The detection algorithms described in Sections 2.3.2 and 2.3.3 use a normalized difference:

$$d(A, B) = \frac{\text{A} - \text{B}}{\text{A} + \text{B}} \tag{2.4}$$

rather than a pure difference between the values. Normalized difference-based methods make the detections more selective and can reduce false-alarms. For example, if the two sets of reflectance values being compared are $\{0.9, 0.7\}$ and $\{0.6, 0.4\}$, a difference calculation would show both equal 0.2 and a detection would be considered.
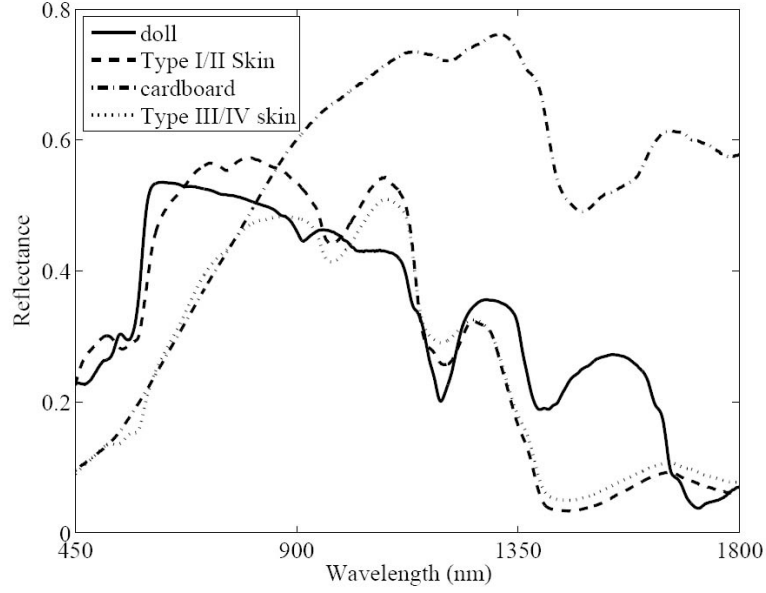
Figure 2.6:   Reflectance measurements of several items that have visible character-
istics of skin, but have dramatic differences in the NIR [23].

A normalized difference considers constant gain factors in the spectrum. The normal-
ized difference calculation results in values of 0.125 and 0.2 respectively showing how
a normalized difference is more selective.

2.3.2   Skin Detection.   The skin detection wavelengths (1080nm in black
and 1580nm in magenta in Fig. 2.1), were chosen for two reasons. First, a normalized
difference is used, which is most effective if the two wavelengths have a large difference
in reflectance for the materials of interest. Furthermore, to reduce false detections
for skin-colored objects, wavelengths in the NIR are used. (Most of the existing skin
detection literature uses visible channels to perform skin detection [1–3,6,10,11,14,17].
In [23], potential skin confusers in the visible region such as dolls, leather, cardboard,
metal, and other materials that "looked" like skin were considered and shown in
Fig. 2.6. A light-skinned baby doll compared to Type I/II skin is fairly close in the
visible wavelengths, but Fig. 2.6 shows that at 1080nm and 1580nm the reflectance is
very different. The same results were shown when cardboard and Type III/IV were
compared.

The normalized difference calculation for skin detection uses:

$$\text{NDSI} = \frac{\hat{\rho}(1080\text{nm}) - \hat{\rho}(1580\text{nm})}{\hat{\rho}(1080\text{nm}) + \hat{\rho}(1580\text{nm})} \tag{2.5}$$

where $\hat{\rho}$ is estimated reflectance. This calculation is performed by using the estimated reflectance values found for the scene imaged at 1080nm and 1580nm. The value solved for is known as the Normalized Difference Skin Index (NDSI). In a simple detector, if this index is between a set bounded threshold, it is passed to a second stage to reduce false-alarms.

2.3.3   False-Alarm Reduction.   As discussed in Section 2.3.2, items that are the same as skin in the visible wavelengths were not confused in the NIR wavelengths used. Nunez did find that certain vegetation in the NIR wavelengths chosen for skin detection did resemble skin's reflectance. Figure 2.1 (Bottom) shows a reflectance measurement of fresh Pinyon pine needles. The similarities between skin and needle-bearing vegetation can be seen if the black and magenta lines are compared. Table 2.3 shows the difference between the reflectance values at 1080nm and 1580nm. When a simple difference is used, the values do not show much dynamic range. In fact, the values of Pinyon pine are greater than Type III/IV and Type V/VI skin, which would result in false-alarms. However, we see the using the normalized difference results in the proper ordering of the values. Still, the values of Type V/VI and Pinyon pine needles are relatively close and could result in false-alarms depending on the thresholds chosen. In a real scenario, the normalized difference calculations do not use "perfect" reflectance values. Three main factors account for these differences. First, the reflectance values of the objects at each pixel are estimated from the camera's data. This process is discussed in Section 2.2.2. Second, the sensor noise of the cameras can change the estimated reflectance values. Third, the cameras are seeing reflections that are illumination and viewing-angle-dependent. With these factors considered, plants look very much like skin in terms of reflectance and result in false detections by the system. This is where the visible wavelengths are used to decrease

Table 2.3:   The differences between the reflectance values of skin and plant with respect to Fig. 2.1.

Material	1080nm	1580nm	Difference	Normalized Difference
Skin Type I/II	0.566	0.074	0.492	0.768
Skin Type III/IV	0.495	0.083	0.412	0.712
Skin Type V/VI	0.422	0.098	0.324	0.623
Pinyon pine Needles	0.541	0.161	0.380	0.542

false-alarms. If the red and green vertical lines are compared between the vegetation and skin, it is seen that skin is more red than green while plants are more green than red. This makes for an easy way to rule out plants and objects that are highly forward scattering (e.g. snow and murky water), which are the most prevalent confusers found to date [24].

False-alarm reduction is the second stage taken to increase the likelihood of a correct detection. false-alarm reduction is based on the normalized difference calculation:

$$\text{NDGRI} = \frac{\hat{\rho}(540\text{nm}) - \hat{\rho}(660\text{nm})}{\hat{\rho}(540\text{nm}) + \hat{\rho}(660\text{nm})}. \tag{2.6}$$

This calculation is performed by using the estimated reflectance values found for the scene imaged at 540nm and 660nm. The value computed is known as the Normalized Difference Green Red Index (NDGRI). In a simple detector, if this index is between a set bounded threshold, the pixel that makes it to this step is declared skin.

2.3.4   Melanin Estimation.   Melanin estimation is executed by using the fact that more melanin results in lower reflection in the visible wavelengths. As melanin level in skin decreases, the reflectance at 800nm (cyan line) significantly decreases and at 1080 (black line) stays relatively the same. This is due to the melanin not absorbing as much energy at these longer wavelengths. Melanin estimation is accomplished using the Near-Infrared Melanosome Index which estimates the Fitzpatrick skin color in Table 2.1 by mapping the percentage of melanin in the tissue (Table 2.2). The

process begins with a ratio between estimated reflectance of 800nm and 1080nm.

$$N(\lambda) = \frac{\hat{\rho}(800\text{nm})}{\hat{\rho}(1080\text{nm})} \qquad (2.7)$$

N(λ) is used to estimate reflectance at 685nm (D per Eqn. (2.8)) which is used to determine melanin percentage (M per Eqn. (2.9)). The constants X in Eqn. (2.8) and C in Eqn. (2.9) are solved using a linear regression (details are provided in [23]):

$$D = X_1 N^2 - X_2 N + X_3 \qquad (2.8)$$

$$\text{M} = -C_1 D^5 + C_2 D^4 - C_3 D^3 + C_4 D^2 - C_5 D + C_7 \qquad (2.9)$$

2.4   Geometric Optics

Geometric optics, treats light as rays and traces these rays through optical systems to solve for important optical system properties such as image/object distance and height, and magnification and focal length. This is a simplification of actual light propagation, because it assumes that an object is imaged perfectly and does not take into consideration the thickness of the lens.

2.4.1   Fundamental Calculations.   Fig. 2.7 shows a single lens with an object and its image. First, there are two "spaces" in this figure. In this case, the object or target is on the left of the lens. As such, this is the object space, where variables are denoted with a subscript 'o'. To the right of the lens is the image space, where variables are denoted with a subscript 'i'. On the object space side, there are several labeled quantities: S_o is the object distance, which is the distance that the object is placed from the lens; X_o is the object height and in this two-dimensional case is the distance from the optical axis to the edge of the object; and f_o is the focal length of the lens. On the image space of the figure, there are the quantities S_i, X_i, and f_i. Here, S_i is the image distance, which is the distance between the lens and the image plane; S_i can be negative which means a virtual image is created. If a scene
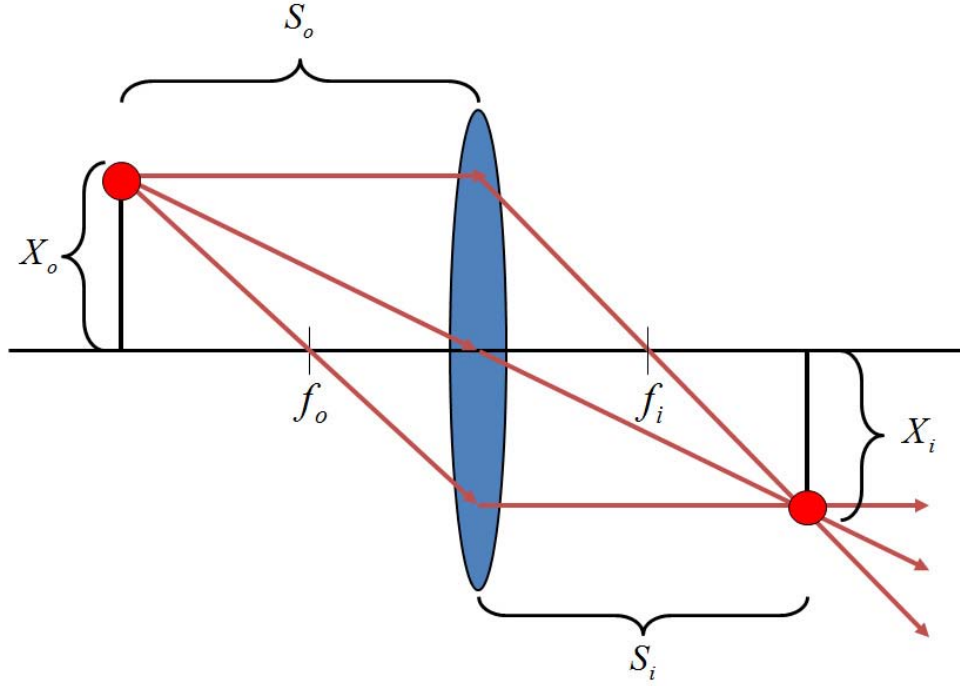
Figure 2.7:   Single lens imaging geometry.

is imaged through the lens in Fig. 2.7, the plane onto which it is imaged would need to be the image distance away for it to be in "perfect" focus. The variable X_i in this two-dimensional case is the height of the image, which is solved for by finding the magnification of the system. Finally, f_i is the focal length of the lens. For single-lens systems, as depicted in Fig. 2.7, the focal lengths are the same, but for systems of more than one lens, there is a front focal length and a back focal length.

Solving for S_i in a single lens setup is accomplished using:

$$S_i = \frac{S_o f}{S_o - f}.$$

(2.10)

The magnification (M) of the system is solved using:

$$M = \frac{-S_i}{S_o} = \frac{X_i}{X_o}$$

(2.11)
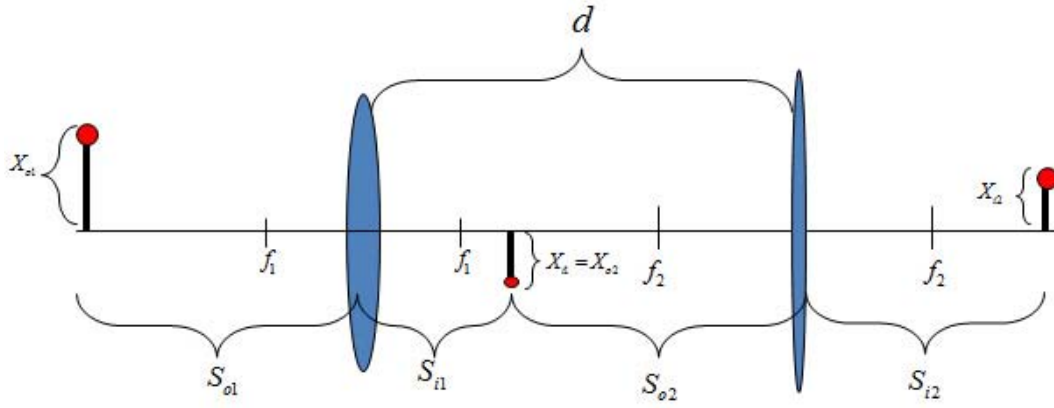
Figure 2.8:   A multiple lens setup labeled with pertinent variables.

and describes how much larger or smaller the objects in the imaged scene are than the objects in object space. If M is negative, then the image is inverted.

A multiple-lens system is shown in Fig. 2.8. When more than one lens is used, the terms discussed above are still valid and a new variable is added. The distance between the lenses is important and is represented by the variable d. To find the image distance S_{i2}, one uses:

$$S_{\text{i2}} = \frac{f_2 d - \frac{f_2 S_{\text{o1}} f_1}{S_{\text{o1}} - f_1}}{d - f_2 - \frac{S_{\text{o1}} f_1}{S_{\text{o1}} - f_1}}. \tag{2.12}$$

The magnification is computed using:

$$M_t = -\frac{f_1 S_{\text{i2}}}{d\left(f_1 - S_{\text{o1}}\right) + f_1 S_{\text{o1}}}. \tag{2.13}$$

2.4.2 Diffraction and Aberrations.   When an object is imaged through a lens it becomes blurred and two important concepts explain why it occurs. The best performance obtainable from an optical system is diffraction limited performance. Diffraction theory treats lights as electromagnetic waves, where geometric optics is the limit in which the wavelength approaches zero. Because light is treated as a wave in diffraction theory it can "bend" around apertures and objects. When light

passes through a circular aperture it is blurred out into an "Airy Disk" pattern which is mathematically modeled by a Bessel function. To solve for the diameter of the central lobe of the Bessel function, where 84% of the energy is located as described as [7] use:

$$d_{\text{spot}} = \frac{2.44\lambda f}{d_{\text{lens}}} \tag{2.14}$$

where the largest wavelength that the individual detector needs to see is λ, the focal length of the lens is f, and the diameter of the lens is d_{lens}.

As stated above, diffraction-limited is the best-case scenario, and aberrations blur out the spot to larger sizes. Monochromatic and chromatic are the two main categories of aberrations. These aberrations result from the shape of the lens, type of lens, materials used in the lens, position of the lens in a system, and/or the wavelength of the light [13].

2.5   Radiometry

Radiometry is the analysis of light energy propagating through space from a source to a detector. It is used to model the system discussed in Chapter III to show the amount of energy incident on a single pixel of each camera. Determining the amount of energy incident on a pixel involves many factors including radiance of the source, reflectivity of the target, attenuation of the light by the atmosphere, distance to detector, and the transmission properties of the optics through which the light must pass. Figure 2.9 shows the steps necessary to model the system from illumination source to focal plane array.

2.5.1   Solid Angle.   An important concept to understand in radiometry is solid angle, measured in steradians. This is the three-dimensional counterpart of the planar angle, measured in radians. Beginning with the definition of radian measure,
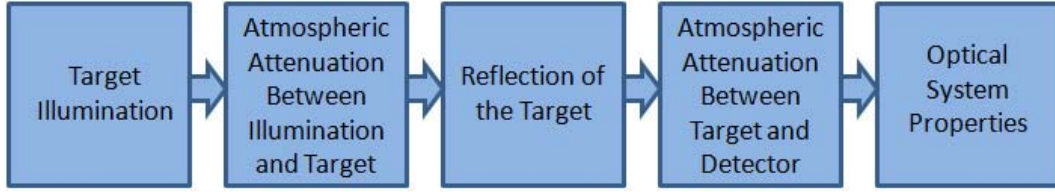
Figure 2.9:   Block diagram showing the necessary steps to model the system from illumination to focal plane array.
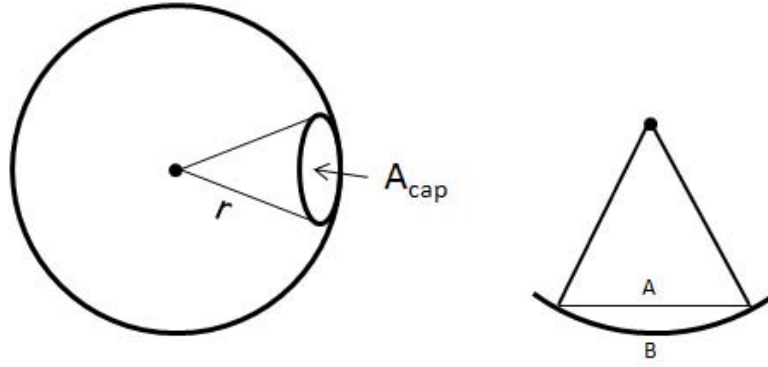
Figure 2.10:   (Left) Diagram showing pertinent variables required to solve for the solid angle (Ω). (Right) Diagram used for demonstrating differences when small angle assumption is used.

radians are a ratio of the arc length s to the arc's radius of curvature r, given by:

$$\theta = \frac{s}{r} \ .$$

(2.15)

With this, any planar angle can be measured in radians without knowing the arc length or radius because the arc length increases at the same rate as the radius for a given angle. Extending radians into three dimensions results in the area of the "cap" (A_{cap}) traced by the radius over the radius squared (r^2):

$$\Omega = \frac{A_{cap}}{r^2}.$$

(2.16)

These variables are shown in Fig. 2.10.

When $r^2 >> A_{cap}$, A_{cap} can be approximated as a chord (line A in Fig. 2.10), rather than taking the curvature into account (line B in Fig. 2.10). This small angle approximation is used throughout the radiometric calculations in this thesis.

2.5.2 Defining Radiometric Quantities. To facilitate discussion, we first describe the variables and their units. When radiometric quantities are represented with watts, they are called joule or energy units and are given the subscript, e. When the radiometric quantities are represented with photons per second, they are called photon units and are given the subscript, p. Radiometric calculations are represented spectrally or totally. Spectral representation yields a calculated quantity per wavelength (μm, nm). When the units are given in total, it means that the spectral measurements have been integrated over a certain region of wavelengths. When the measurements are represented spectrally, they can be converted between the energy and photon units. The conversion can only be accomplished when the measurements are spectral, because the conversion is wavelength-dependent, as illustrated:

$$\text{EnergyQuantity}(\lambda) = \text{PhotonQuantity}(\lambda) \, \frac{hc}{\lambda} \qquad (2.17)$$

where h is Planck's constant, c is the speed of light, and λ is the wavelength.

A light ray is often described by the energy it contains (Q) and the rate of the energy received (the flux, Φ) which is a measurement of the light ray's power. The most easily understood radiometric quantities are those that involve flux density, such as irradiance (E) and exitance (M) which are flux per unit area either incoming or outgoing, respectively. The next quantity of interest is intensity (I_e) which is flux per unit solid angle.

The most fundamental quantity is radiance as the other quantities are derived directly from it. Radiance is defined as the amount of power radiated per unit projected source area per unit sold angle [7]. Table 2.4 shows the International System of Units (SI) for the radiometric quantities used in this thesis.

Table 2.4: Radiometric Quantities

Quantity	Energy Units		Photon Units	
	Symbol	Units	Symbol	Units
Energy	Q_e	joule	Q_p	photon
Flux	Φ_e	watt	Φ_p	$\frac{\text{photon}}{\text{s}}$
Intensity	I_e	$\frac{\text{watt}}{\text{sr}}$	Q_p	$\frac{\text{photon}}{\text{s sr}}$
Exitance	M_e	$\frac{\text{watt}}{\text{cm}^2}$	M_p	$\frac{\text{photon}}{\text{s cm}^2}$
Irradiance	E_e	$\frac{\text{watt}}{\text{cm}^2}$	E_p	$\frac{\text{photon}}{\text{s cm}^2}$
Radiance	L_e	$\frac{\text{watt}}{\text{sr cm}^2}$	L_p	$\frac{\text{photon}}{\text{s sr cm}^2}$
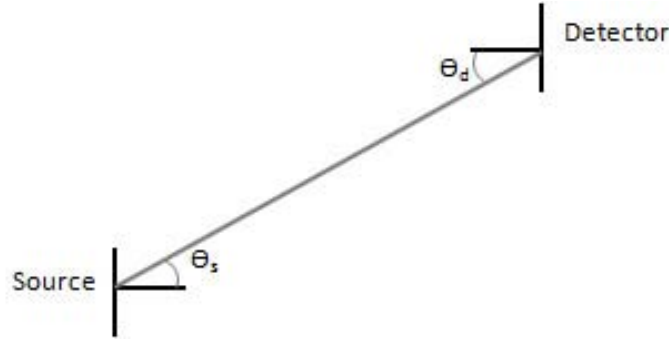
Figure 2.11: Diagram showing locations of θ_d and θ_s.

2.5.3 Solving for Radiometric Quantities. Since the small-angle approximation is assumed, the radiance (L) can be written in its non-differential form:

$$L = \frac{\Phi}{A_s \cos\left(\theta_s\right) \Omega_d} \tag{2.18}$$

where Φ is the flux from the source, A_s is the area of the source, Ω_d is the solid angle subtended by the detector, and θ_s is the angle formed by the normal to the source and the optical path. Figure 2.11 shows θ_s and later mentioned θ_d in a diagram to show their locations. (For the purpose of showing how the quantities can be computed, neither photon or joule units are explicitly specified.)

From the radiance (L) in Eqn. (2.18), the flux (Φ) is computed by:

$$\Phi = L A_s \cos\left(\theta_s\right) \Omega_d \ . \tag{2.19}$$

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From flux (Φ), the intensity (I) and exitance (M) are solved for as:

$$I = \frac{\Phi}{\Omega_d} = L\cos\left(\theta_s\right) A_s \quad \text{and} \tag{2.20}$$

$$M = \frac{\Phi}{A_s} = L\cos\left(\theta_s\right) \Omega_d \quad . \tag{2.21}$$

To find the irradiance (E), the solid angle (Ω_d) is divided into its constituent components:

$$\Omega_d = \frac{A_d\cos\left(\theta_d\right)}{R^2} \quad \text{and} \tag{2.22}$$

$$E = \frac{\Phi}{A_d} = \frac{L\cos\left(\theta_d\right)\cos\left(\theta_s\right) A_s}{R^2} \quad . \tag{2.23}$$

The second important assumption is that the source is lambertian. This means that the source's radiance (L) is independent of the viewing angle (θ_s). Under this assumption, the relationship between radiance (L) and exitance (M) is:

$$M = \pi L \quad . \tag{2.24}$$

2.5.4   *Modeling Illumination Sources.*   The radiance of a source is represented as a blackbody source. This type of source emits radiation at the theoretical maximum with respect to the source temperature and the wavelength. The expression for joule radiance (L_e) is:

$$L_e(\lambda, T) = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda kT}} - 1\right)} \left[\frac{W}{\text{cm}^2 - \text{sr} - \text{nm}}\right] \tag{2.25}$$

where h is Planck's constant, c is the speed light, k is Boltzmann's constant, and T is the temperature in Kelvin.

Figure 2.12 shows the blackbody curves for three different temperatures. The highest temperature modeled is that of the sun, 5950K (red). The 4500K temperature (green) is an intermediate step to show how the curves progress as the temperature
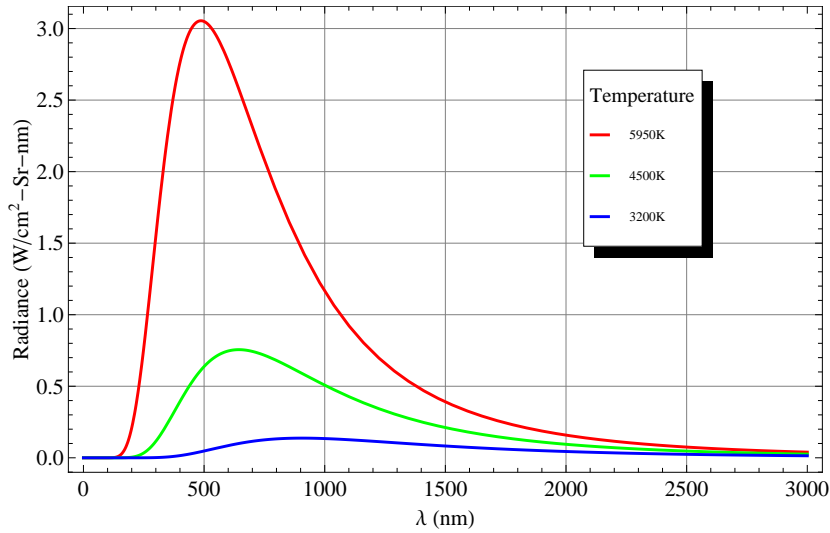
Figure 2.12:   Three radiance blackbody curves with varying temperatures. The sun is shown in the red curve with a temperature of 5950K. The 4500K temperature, in green, is an intermediate step to show how the curves progress as the temperature changes. The ASD Pro Lamps used in the study is represented with a 3200K black body curve.

changes. The color temperature of the lamps used in Chapter IV for the indoor study are 3200K. Because the lamps are not perfect blackbody radiators, (so-called graybodies), the color temperature given is used to model the blackbody curve of the source [7].

   2.5.5   Atmospheric Attenuation.   The atmospheric transmission is an important aspect to make the model as realistic as possible. The amount of attenuation the atmosphere has on an illumination source is dependant on the distance it has to travel. All the other atmospheric properties are taken into consideration in the extinction plot, shown in Fig. 2.13[1]. It is made for winter WPAFB atmosphere with default visibility (∼17km) in climatological aerosols. The extinction coefficient is transformed

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[1]This plot was created by Dr. Steven Fiorino, Atmospheric Physicist, with Laser Environmental Effects Definition and Reference (LEEDR).
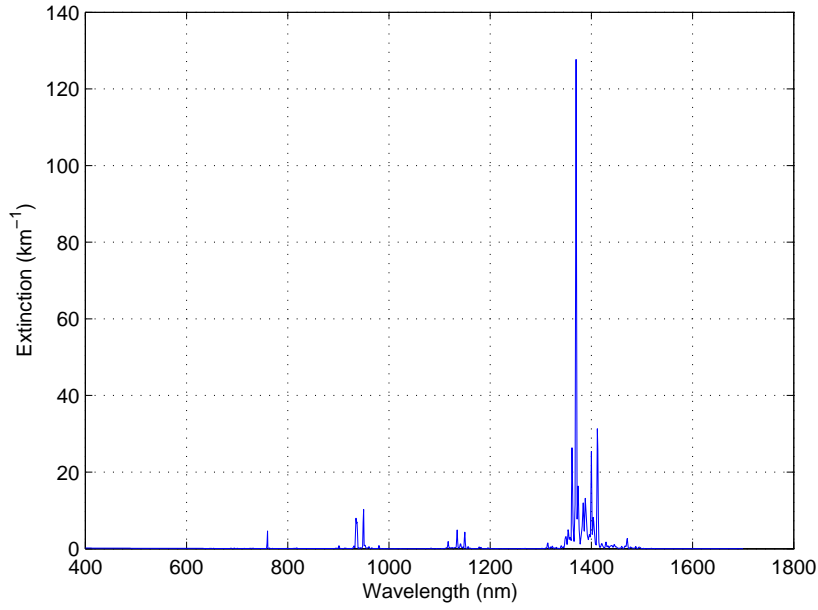
Figure 2.13:   Atmospheric extinction created in Laser Environmental Effects Definition and Reference (LEEDR). This is used along with beer's law to estimate atmospheric transmission.

into atmospheric transmission using Beer's law:

$$\tau(\lambda) = e^{-\alpha(\lambda)\ell} \tag{2.26}$$

where $\alpha(\lambda)$ is the spectral extinction in Fig. 2.13 and ℓ is the distance in km between the source and detector. Two examples of using Beer's law and how atmospheric transmission changes with respect to distance are shown in Fig. 2.14.

2.5.6 Converting Photons to Electrons.   Once the light from the illumination source passes through the atmosphere and is reflected off the target, additional attenuation occurs due to the system components. Every lens, mirror, and filter has a transmission that needs to be taken into account to model the system appropriately. Since the end goal is to model the data numbers for each image, the number of photons that create electrons needs to be determined. This count of photons is directly related to the data numbers. Once the energy values at each pixel are in photons per
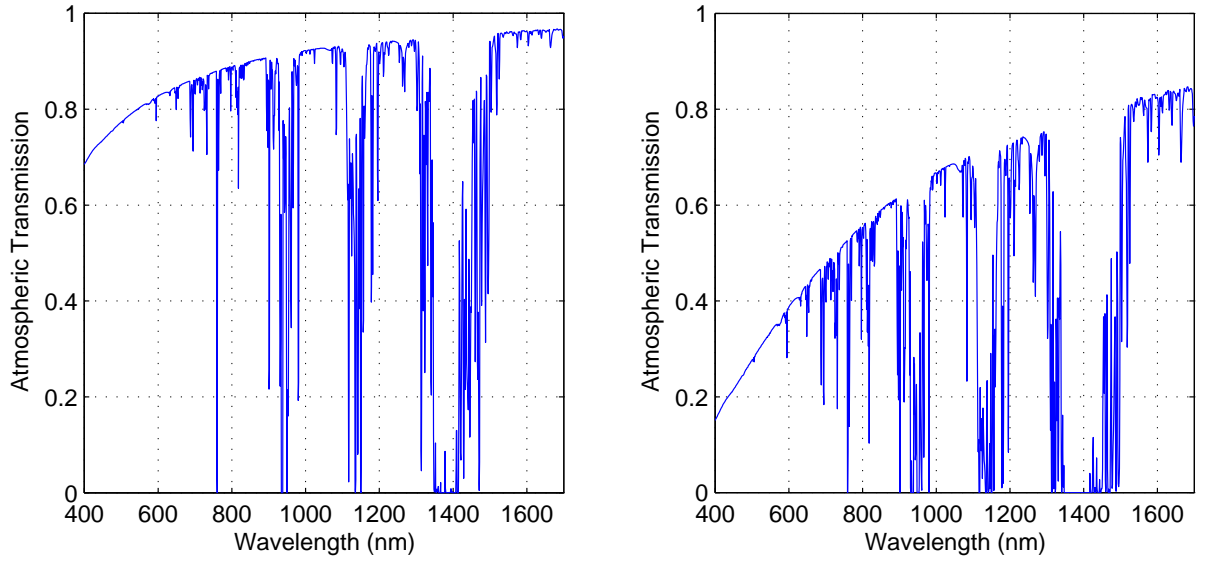
Figure 2.14:   Two examples of using Beer's law and how atmospheric transmission changes with respect to distance. (Left) Distance between detector and source 2km. (Right) Distance between detector and source 10km.

second, they are multiplied by the integrations times of the cameras to determine how many photons are hitting the array in each frame. To determine how many photons create electrons on average, the quantum efficiency of each camera is used. Dereniak defines quantum efficiency as the efficiency of converting a photon to an electron, or the number of independent electrons produced per photon [7].

2.6   Summary

First, the background necessary to understand the features exploited and methods used for skin detection which are necessary to build the system are discussed. Second, the reflectance properties of human skin are discussed to give the reader a basis of why certain wavelengths were chosen. The algorithms used to perform the detections are discussed to show how the images are processed. Third, an overview of the geometric optics used to solve for lens focal lengths and diameters is completed. Lastly, a radiometry overview is accomplished to discuss how the model is created for

this thesis. Now that the background is reviewed the methodology behind designing the system and the model are discussed.
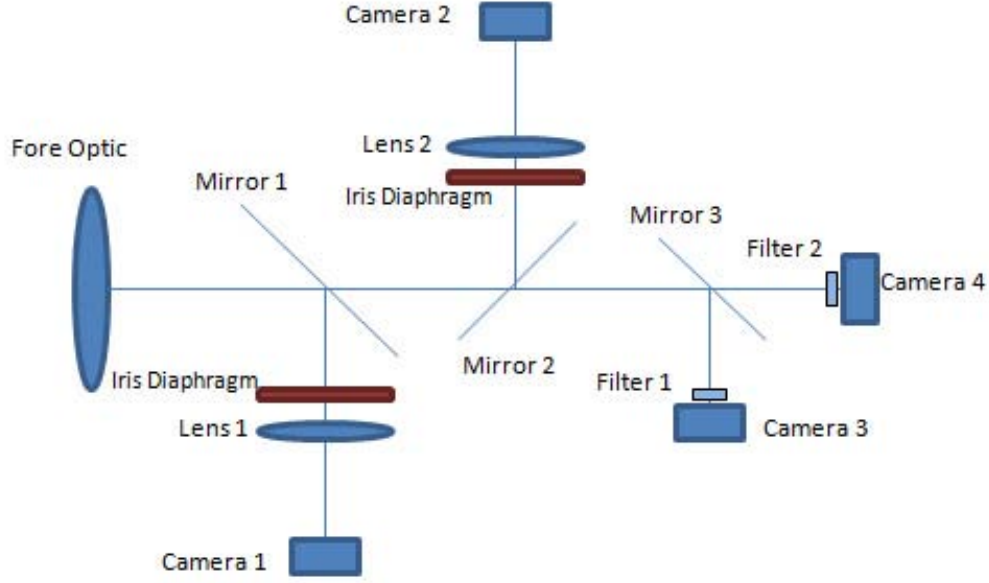
Figure 3.1:   Block diagram for the monocular skin detection, melanin estimation, and false-alarm suppression camera system developed in this thesis.

III. Methodology

The construction of the system is based on the essential components depicted in Fig. 3.1: detectors, fore optic, secondary lenses, iris diaphragms, dichroic mirrors, and filters. The remainder of the chapter describes and characterizes each component in the system depicted in Fig. 3.1. Near-infrared (NIR) and visible (VIS) cameras are necessary to do the skin detection, melanin estimation, and false-alarm suppression. The specifications necessary and the chosen cameras are discussed. Lenses need to be chosen for the fore optic and correcting lenses. The beamsplitters' size and transmission are discussed. The transmission of the filters used to narrow down the broadband energy are discussed as well.

3.1   Camera Selection

As discussed early in Section 2.1, this system requires NIR and VIS wavelengths to perform the necessary detection, false-alarm suppression, and melanin estimation tasks. These cameras need to record at least 1fps with an external trigger so every camera can image the scene at the same time. The goal is to find cameras that have

Table 3.1:   Specifications for the Goodrich SU640KTSX-1.7RT.

Parameter	Value
Spectral Response	900nm-1700nm
Pixel Pitch	25μm
Array Format	640×512
Image Depth	12 bit
Frame Rate	30fps
Camera Body Size(H $\times$ W $\times$ D)	2.1in $\times$ 2.1in $\times$ 2.55in

the capability to do 30fps as the algorithm speed increases. High spatial resolution is another important aspect needed to detect a person from ∼710ft away. In Fig. 3.1, the VIS cameras are *Camera 1* and *Camera 2* and the NIR cameras are *Camera 3* and *Camera 4*.

3.1.1   Near-Infrared Cameras.   A limited number of InGaAs near-infrared (NIR) cameras are available commercially. We chose the Goodrich SUI640KTSX-1.7RT High Sensitivity InGaAs NIR Cameras due to performance characteristics and compact size. As such, the design of the system is based on them. Table 3.1 shows the specifications of the Goodrich camera relevant to this thesis. The camera response in Fig. 3.2 was experimentally measured with the use of an Oriel Lamp and a calibrated monochromator. To make sure the camera is not saturating the images used to create the plot are checked for data number values of 4095. The absorption feature at 1380nm is due to atmospheric water absorption [29]. From Fig. 3.2, one can see that the skin detection bands at 1080 and 1580nm are well within the camera's response, as indicated with the vertical lines.

3.1.2   Visible Cameras.   Since false-alarm reduction uses 540nm (green line in Fig. 2.1) and 680nm (red line in Fig. 2.1), as specified in Section 2.1, a common visible camera is used. There were a few approaches used to find a camera that works for the false-alarm suppression. The first approach is to find a visible camera that has the same pixel size as the Goodrich Cameras. This makes the pixel-by-pixel comparison for the detection task simple. Since the Goodrich cameras have 25μm
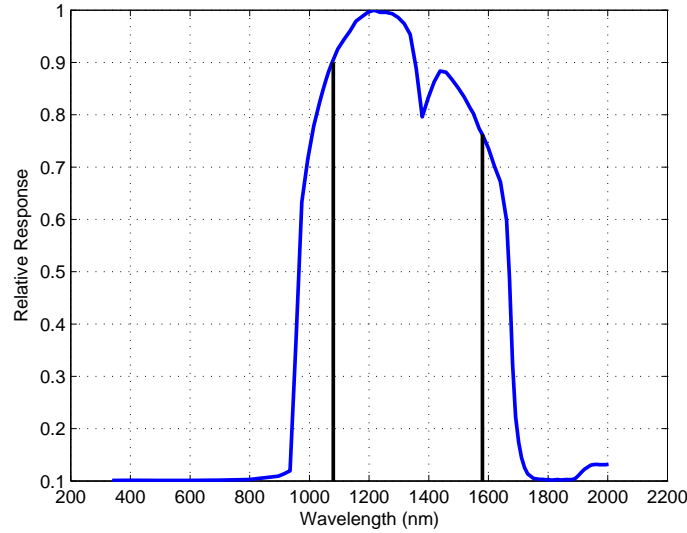
Figure 3.2: Relative response of the Goodrich SU640KTSX-1.7RT High Sensitivity InGaAs short wave infrared camera. The absorption feature at 1380nm is due to atmospheric water absorption. Skin detection bands are marked with vertical lines.

pixels, the other system cameras need to match. Research found that it is difficult to find 25μm pixel silicon cameras. Because one could not be located, a second approach was necessary. This second approach attempts to find a pixel size that, when averaged together, resulting in 25μm superpixels. For example, using a 6.25μm pixel camera averaging 4×4 pixels would make an equivalent 25μm pixel. The trade off by grouping pixels is that a larger focal plane array is necessary to match the Goodrich camera's 640×512 array. Table 3.2 shows how close typical pixel sizes are grouped to estimate 25μm.

If a perfect 25μm superpixel cannot be created, the pixel grouping that is closest should be used. The problem at first is to get this larger (or smaller) pixel to be spatially registered with the 25μm pixel. This is fixed by moving the cameras relative to an in focus image in order to image their pixels to the same size as the 25μm pixels. Fig. 3.3 shows the distance a camera needs to be moved relative to where a well focused image would appear so that the imaged pixels are 25μm pixels at 707ft.

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Table 3.2: Pixel sizes used to calculate how far camera must be moved to get same imaged size as 25μm.

Pixel Size μm	Group Size Pixel by Pixel	Superpixel Size μm	Array Size To Match 640×512 Pixel by Pixel
7.4	3×3	22.2	1920×1536
6	4×4	24	2560×2048
12	2×2	24	1280×1024
24	1×1	24	640×512
9	3×3	27	1920×1536
6.45	4×4	25.8	2560×2048
5.2	5×5	26	3200×2560
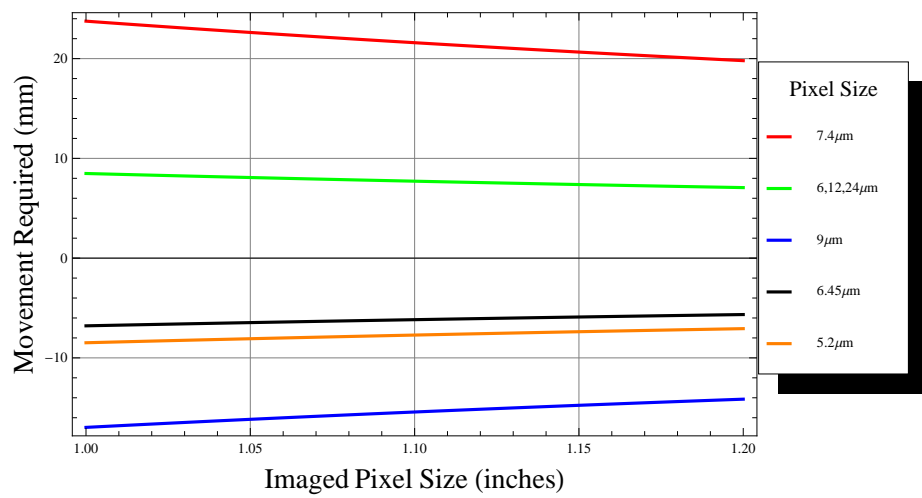
Figure 3.3: Distance and direction a camera needs to move so that its pixel size is the same as the Goodrich camera. The difference is calculated from a 150mm focus. Negative numbers refer to the camera moving away from the lens while positive is moving towards.

A negative number refers to the camera moving away from the lens, while positive is toward the lens.

Moving the cameras could result in the image being slightly out of focus, but with the averaging taking place, it might not make a significant difference. To theoretically see if the image is still in focus, a depth of focus calculation is accomplished and shown in Fig. 3.4. As defined in [9], depth-of-focus is the amount of defocus corresponding to being out of focus by one quarter wavelength. This calculation uses the
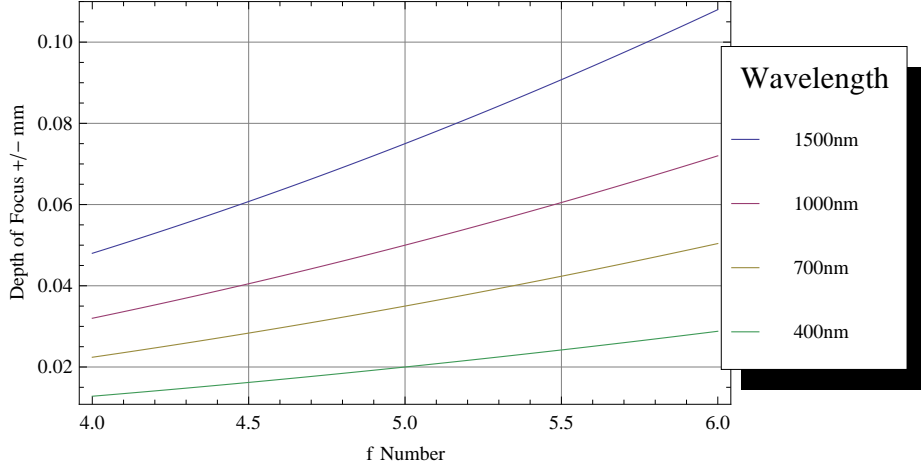
Figure 3.4: The depth of focus calculation with respect to f-number.

Rayleigh criterion which states that if the optical path distance is less than or equal to a quarter wavelength, then it is still considered diffraction-limited [9]. Figure 3.4 demonstrates how far each of the four cameras can move and still theoretically stay in focus. Figure 3.4 shows the detectors can move only fractions of a mm to stay in focus, while Fig. 3.3 shows that the detectors need to move several mm to image to the right size. This means that the images would most likely be out of focus. As such, the following approach is considered.

The last approach uses a second lens to image the pixels of the visible camera to the same size pixels as the Goodrich cameras. (The lens is discussed in more detail in the next section). The advantage of this design is that the number of cameras one can use for the visible wavelengths is substantially extended. This extension includes any color camera that has at least as many pixels as the Goodrich focal plane array and that can be externally triggered. A camera that matched these specifications is the ThorLabs DCC1645C High Resolution USB2.0 CMOS camera. A picture of this camera is shown in Fig. 3.5 and the specifications in Table 3.3. The responsivity provided by the vendor is shown in Fig. 3.6.

The array format works out well, because the pixels can be imaged out to half the size of the 25μm pixels. This means that, not only can the visible camera be used

Figure 3.5: Picture of the ThorLabs High Resolution USB2.0 CMOS Series Cameras.

Table 3.3: Important specifications of the ThorLabs DCC1645C.

Parameter	Value
Spectral Response	Visible light
Format	RGB
Pixel Pitch	3.6μm
Array Format	1280×1024
Image Depth	10 bit
Frame Rate	25fps
Camera Body Size(H $\times$ W $\times$ D)	1.88in $\times$ 1.68in $\times$ 1.00in

for the false-alarm reduction discussed above, it provides a higher resolution image of the imaged scene. These higher resolution snapshots can be triggered and saved by the user or whenever skin is detected. The small size of this camera is additionally important since there is little room to fit the four cameras required for this system.

Due to the reasons discussed above, a second ThorLabs camera is chosen for the melanin estimation. Since RGB is not necessary for the melanin estimation task, the DCC1545M High Resolution USB2.0 CMOS *monochrome* camera is chosen. Table 3.4 shows the specifications for the camera and the responsivity given by the vendor is shown in Fig. 3.7. (Note that the response of the DCC1645C is better than that of
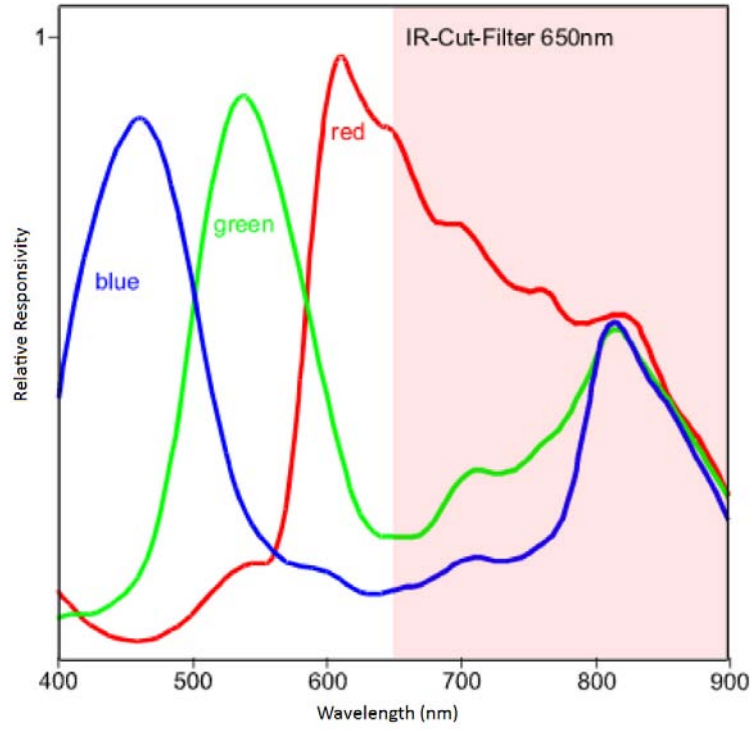
Figure 3.6:   Relative Response of the ThorLabs DCC1645C.

the DCC1545M at 800nm. However the DCC1645C has an IR cut filter built into the camera while the DCC1545M does not.)

3.2   Lens Selection

The complete system requires three lenses. The first is a 150mm focal length lens used as the single fore optic (Fore Optic in Fig. 3.1). The second lens (Lens 1

Table 3.4:   Important specifications of the ThorLabs DCC1545M.

Parameter	Value
Spectral Response	Visible light
Format	Monochrome
Pixel Pitch	5.2μm
Array Format	1280×1024
Image Depth	10 bit
Frame Rate	25fps
Camera Body Size(HxWxD)	1.88in x 1.68in x 1.00in
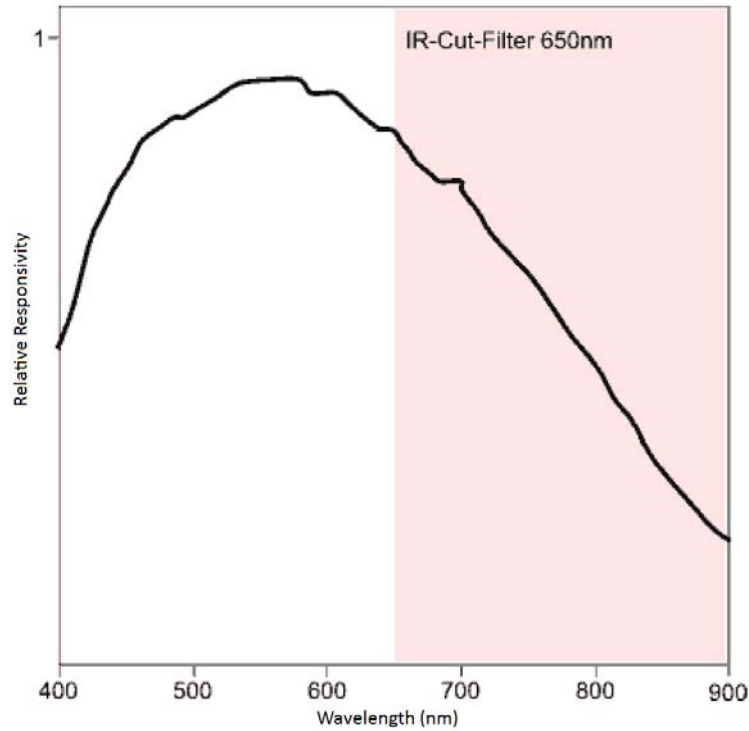
Figure 3.7:   Relative Response of the ThorLabs DCC1545M. Even though the plot shows an IR cut filter this camera model does not have one.

in Fig. 3.1) is placed in front of the ThorLabs RGB camera correcting for its pixel size difference. The third lens (Lens 2 in Fig. 3.1) is placed in front of the ThorLabs monochrome camera to correct for its pixel size difference. Due to the specifications described in Section 1.1, the lenses were selected to image the pixels of each camera to no larger than 2×2 inches at 707ft.

3.2.1   Fore Optic (Front Lens).   Proper selection of the fore optic is difficult as there are several considerations one must balance. First, as stated above, the pixels of each camera need to be imaged to at most 2×2 inches to get the largest FOV without losing spatial resolution. Second, the image distance needs to be large enough to fit the three dichroic mirrors between the cameras. Lastly, the system needs to be kept as close to diffraction-limited as possible.

Because the object distance is relatively far away, the focal length is approximately the same as the image distance. Figure 3.8 shows the image distance with

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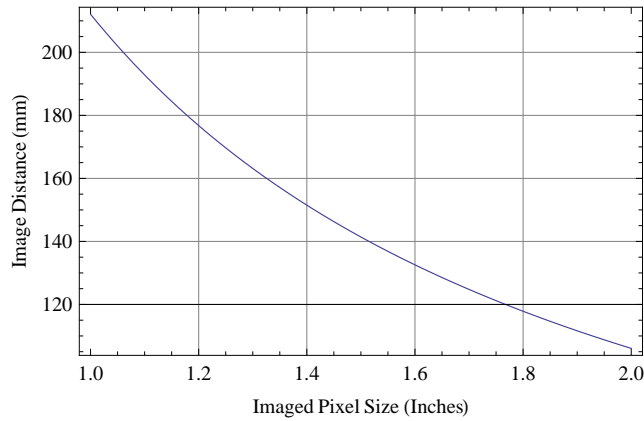
Figure 3.8: The image distance with respect to imaged pixel size for a 25μm pixel calculated with the object distance set at 707ft.

respect to the size of the imaged pixel for an object imaged at 707ft. As seen in Fig. 3.8, a 2×2 inch imaged pixel results in an image distance of 106.1mm (4.18in). This distance is far too small for the placement of the required dichroic mirrors behind the lens (as shown previously in Fig. 3.1). For more space between the lens and the cameras, the imaged pixel must be smaller as indicated in Fig. 3.8.

The mirrors sizes are designed to support up to a 50mm diameter lens. The final solution has three different sized mirrors in the chain and is discussed in more detail in Section 3.3. To make sure there is enough room to fit all the mirrors with holders, each mirror is considered the same size, so a focal length of 150mm is necessary to image onto the final camera in the chain (see Fig. 3.9). Using the 150mm focal length and object distance of 707ft, the imaged pixel size decreases to 1.41in, which increases the spatial resolution of the camera. Figures 3.10 and 3.11 show how many more "pure pixels" are seen by the cameras with the 1.41in imaged pixel size. The figures are to scale and the same head and hand size are used as described in Table 1.1. An increase from 7 to 18 pixels on the head and 6 to 8 pixels on the hand show that the smaller pixel size benefits the detection. Because this lens is directly imaging onto the Goodrich camera, its diffraction-limited spot diameter needs to be less than 25μm.
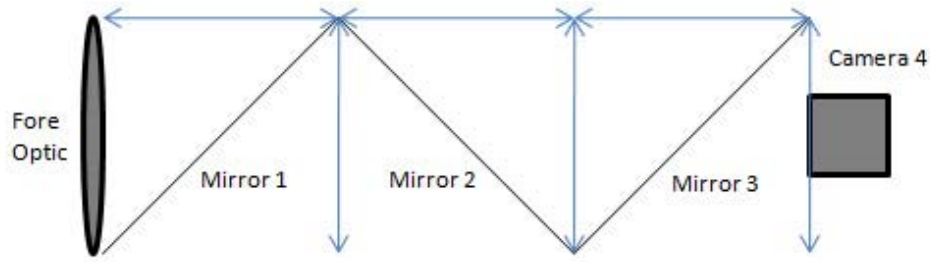
Figure 3.9:   System setup assuming the three dichroic mirrors are the same size in order to approximate the minimum focal length that leaves enough room for the mirrors. All blue arrows are 50mm in length.
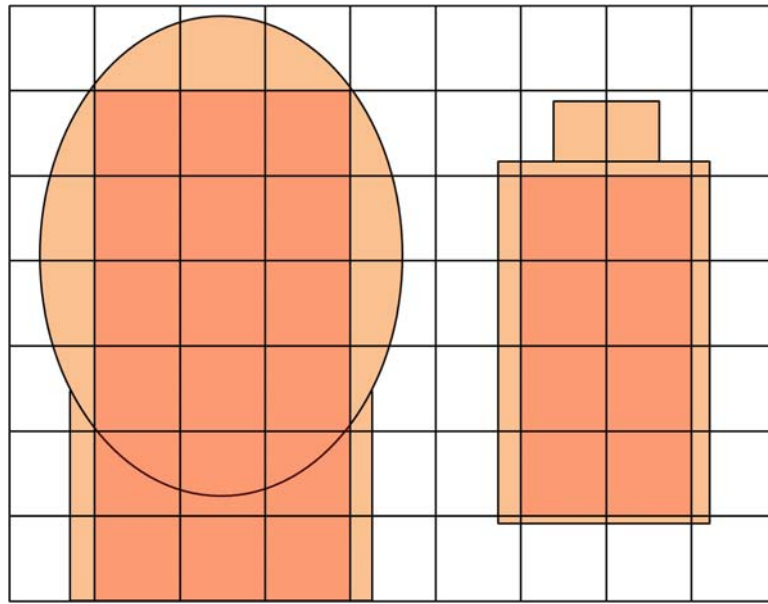
Figure 3.10:   To scale 1.41in pixels corresponding to the measured head and hand size. This shows the best case scenario with the pure skin pixels shown in red.

Using the lens specifications in Table 3.5 and Eqn. (2.14) the diffraction spot size is solved as 15.37μm, which meets the requirement.

Off-the-shelf optics are used for the monocular skin detection system developed in this thesis. The Newport PAC075 achromatic doublet met the previously stated requirements and is chosen for the fore optic. An achromatic doublet is used because it is made to correct for the refraction differences in the visible spectrum. The visible light energy is the broadest spectrum sent to one camera, so the largest chromatic aberrations occur here. The other cameras receive smaller spectral bands so chromatic
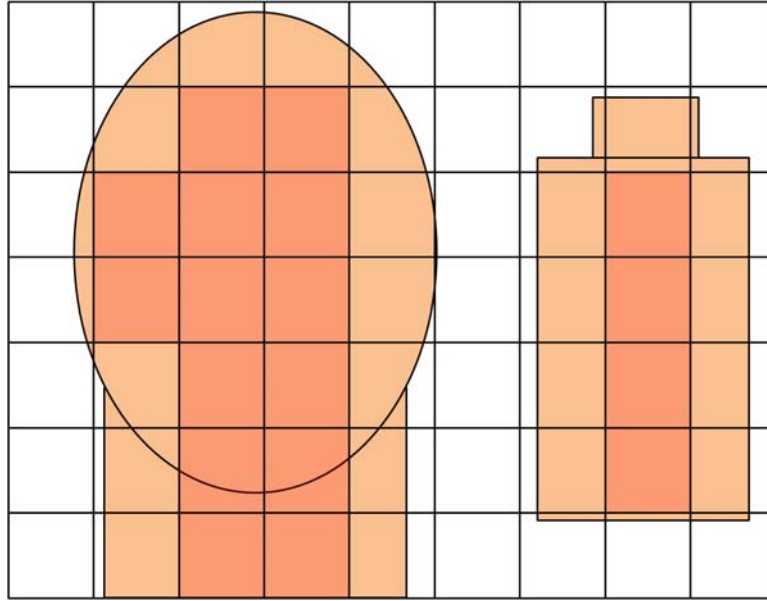
Figure 3.11:   To scale 1.41in pixels corresponding to the measured head and hand size. This shows the worst case scenario with the pure skin pixels shown in red.

Table 3.5:   Specifications of the PAC075 Newport Achromatic Double lens.

Parameter	Value
Airy Disc Size @ 1.6μm	15.37μm
Focal Length	150mm
Diameter of Optic	38.1mm
f/#	3.93

aberrations should affect their images less. The specifications of the Newport Optics lens is shown in Table 3.5.

3.2.2 Color Camera Lens.   There are two choices of magnification for the ThorLabs cameras to make a pixel-by-pixel comparison possible with the Goodrich cameras. The pixels from the ThorLabs cameras can be imaged the same size as the Goodrich cameras, or they can be imaged smaller to have a higher spatial resolution. Due to the array format of the camera, discussed in Section 3.1, there are enough pixels to image with twice the spatial resolution and still have the same FOV. This results in a 4:1 pixel ratio between the ThorLabs and Goodrich cameras. The specifications that need to be determined are the distance between the fore optic and this second
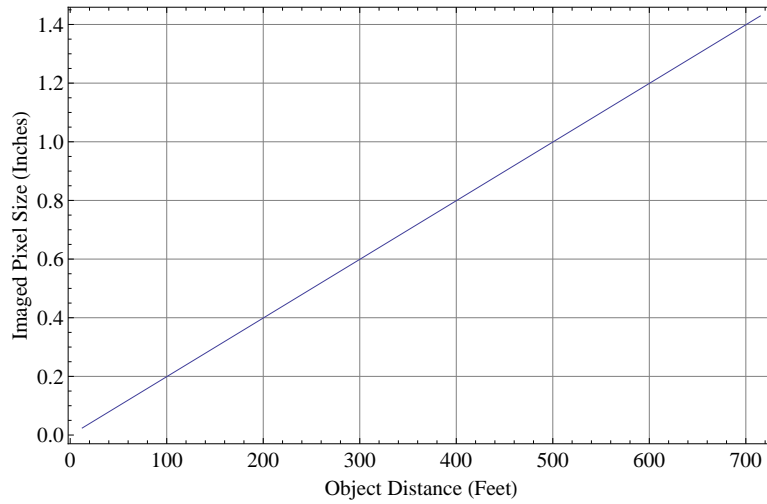
Figure 3.12:   The imaged size of the 25μm pixels at different target distances. These
are calculated using a 150mm focal length lens.

lens, and the focal length of the second lens. The distance between the fore optic
and the second lens is calculated based on a laboratory setup so the results are easily
verified. First the imaged size of the 25μm Goodrich pixels need to be known. This is
accomplished using Eqn. (2.10) and (2.11) using the 150mm focal length of the chosen
fore optic. Figure 3.12 shows how the size of the imaged pixel changes as the object
gets further away from the fore optic.

The important distances in Fig. 3.12 to consider are 31ft and 707ft, which are the
laboratory and operational distances, respectively. The laboratory scenario produces
an image with pixel sizes of 0.061 in, while the operational scenario produces an image
with pixel sizes of 1.41in. The next step is to divide these numbers in half so the 4:1
pixel ratio is taken into consideration.

With the "half image size" determined, the distance between the fore optic
and the color camera lenses as well as the focal length of the color camera lens is
determined. The magnification required to make the image of the 3.6μm pixels the
correct size (0.0305 for 31ft and 0.705 for 707ft) is determined using Eqn. (2.11). Using
the two lens configuration, the magnification is set equal to the two-lens magnification
equation [Eqn. (2.13)].
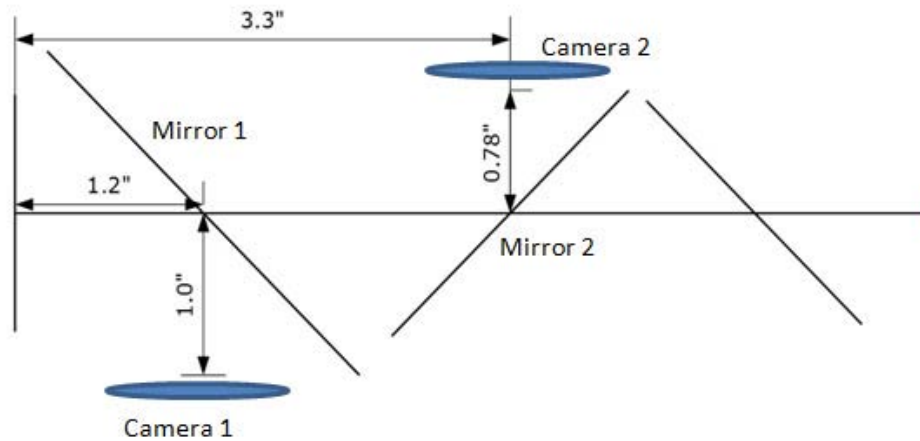
Figure 3.13:   This figure demonstrates a safe distance between the fore optic and correcting lenses so they will not hit the mirrors.

To make sure the second lens does not hit the mirrors, it needs to be at least 2.2in from the front lens (see system layout in Fig. 3.13). Figure 3.14 shows what focal lengths are necessary to maintain the proper magnification and the resulting image distance as the distance between the lenses is varied. A 30mm focal length lens does not hit the mirror and leaves enough room to move the lens closer to image targets further away than 707feet. Using a 30mm focal length, the distances between the fore optic and the second lens are 3.08in for a target 31ft away (red line) and 2.98in for a target 707ft away (blue line). These target distances result in image distances of 0.841 and 0.843in, respectively. This shows that for any operational distance at which the object is placed, the distance necessary for the lenses and cameras to move is relatively small. This keeps the system compact for a wide variety of scenarios for which it might be used.

The LB1757-A Bi-Convex Lens from ThorLabs is chosen for this camera. The specifications of the lens are shown in Table 3.6. As Fig. 3.15 demonstrates, the coating on this lens is specifically designed for efficiently transmitting 425-675nm wavelengths at >96.7%.

3.2.3   Monochrome Camera Lens.   To ensure that the lens for the monochrome camera does not hit the second dichroic mirror, the distance needs to be at least 4.08in
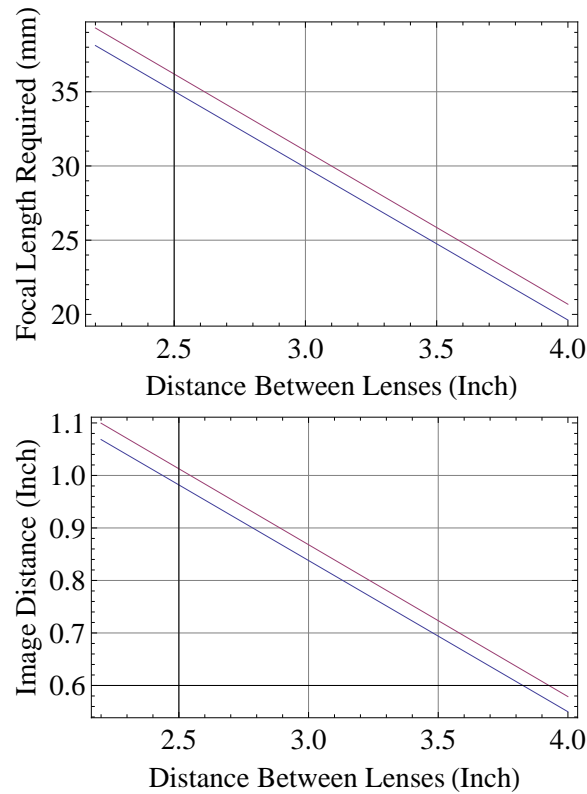
Figure 3.14:   (Top) This plot shows what distances between lenses and focal lengths are necessary to get the proper magnification of the pixels. (Bottom) Image Distance of two lens optical chain. (Red) Object 31ft away from front lens. (Blue) Object 707ft away from front lens.

from the fore optic. This is shown in the system layout diagram, Fig. 3.13. Figure 3.16 shows what focal lengths are necessary to maintain the proper magnification and the resulting image distance as the distance between the lenses is varied. A 30mm focal length lens does not hit the mirror and leaves enough room to move the lens closer to image targets further away than 707feet. Using a 30mm focal length, the distances between the fore optic and the second lens are 4.34in for a target 31ft away (red line) and 4.25in for a target 707ft away (blue line). These target distances both result in image distances of 0.69in. This shows that for any operational distance at which the object is placed, the distance necessary for the lenses and cameras to move is relatively small. This keeps the system compact for a wide variety of scenarios for which it might be used.

Table 3.6:   Specifications of the ThorLabs LB1757-A Lens.

Parameter	Value
Focal Length	30.0mm
Diameter	25.4mm
F#	1.18
Glass	BK7
Coatings	Anti-reflective Visible
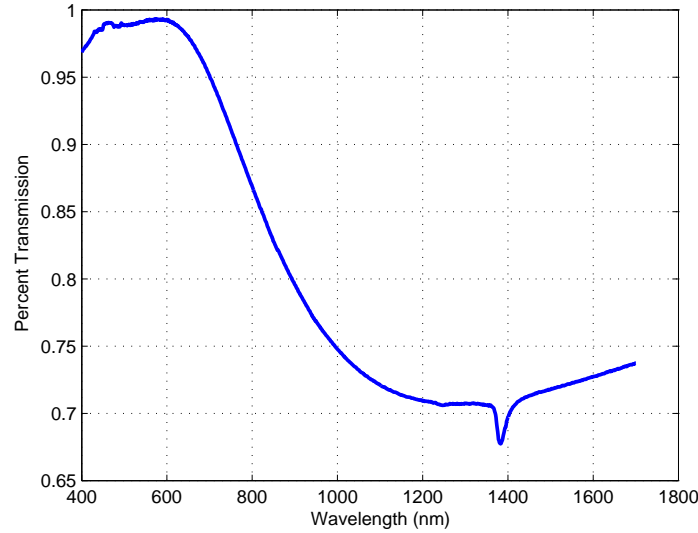
Figure 3.15:   Transmission of the ThorLabs LB1757 A coated lens measured by ThorLabs using a spectrophotometer.

The LB1757-B Bi-Convex Lens from ThorLabs is chosen for this camera. The specifications of the lens are shown in Table 3.7. As Fig. 3.17 demonstrates, the coating on this lens is specifically designed for efficiently transmitting 775-825nm wavelengths at >98.57%.

3.3 Dichroic Mirrors

Figure 3.1 shows the location of the dichroic mirrors in the system. These mirrors are designed specifically to properly divide the spectrum for use in this system. The reflection and transmission properties of the specified wavelengths need to be as high as possible so that detections can be accomplished even under low illumination
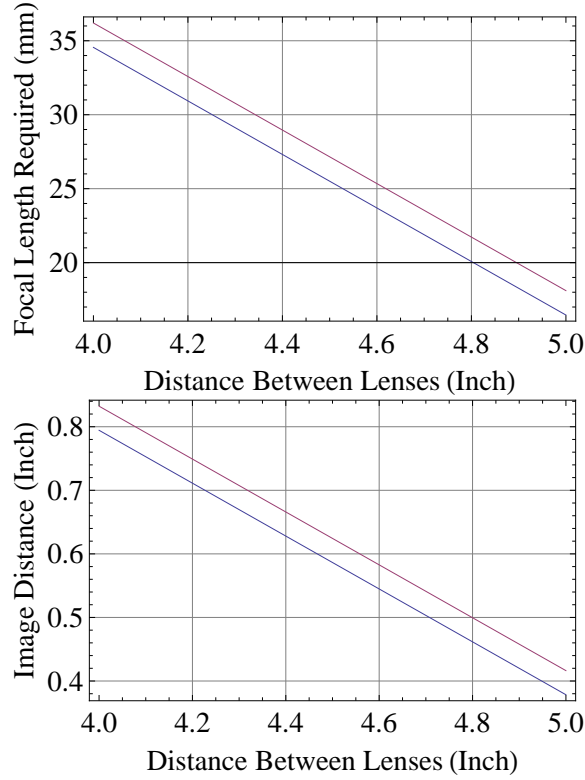
Figure 3.16:   (Top) This plot shows what distances between lenses and focal lengths are necessary to get the proper magnification of the pixels. (Bottom) Image Distance of the two-lens optical chain. (Red) Object 31ft away from front lens. (Blue) Object 707ft away from front lens.

situations. Different light division methods were considered, most were not efficient enough for use in skin detection, due mostly to the already low solar illumination at 1580nm. If the system is only used during bright days, then off-the-shelf cold mirrors and pellicles might work adequately. For this research, we wanted to push the search and rescue capability to its limits, so we chose to use dichroic mirrors.

The mirrors need to meet two size specifications. First, the mirrors need to reflect the entire image from the lens since this system supports at most a 50mm lens. Second, the mirrors must fit in the 150mm ($\sim$6in) space between the fore optic and *Camera 4*. Fig. 3.18 shows the model of the system tracing relevant rays of light.

To meet the specifications above, the mirrors need to be 2.9, 2.2 and 2.0in squares. Furthermore the mirrors need to allow all polarizations to transmit and

Table 3.7:   Specifications of the ThorLabs LB1757-B Lens.

Specification	Value
Focal Length	30.0mm
Diameter	25.4mm
F#	1.18
Glass	BK7
Coatings	Anti-reflective NIR
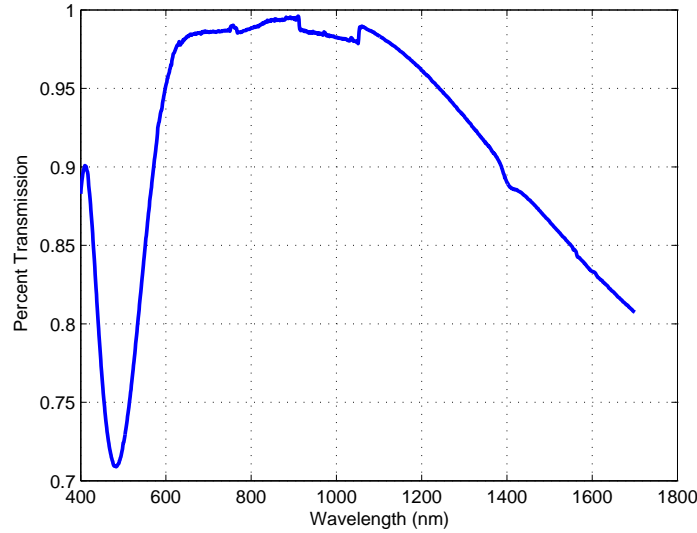
Figure 3.17:   Transmission of the ThorLabs LB1757 B coated lens measured by ThorLabs using a spectrophotometer.

reflect respectively. (Skin detection does not necessarily require polarized light to work and this aspect has not been researched to date). Table 3.8 shows the wavelengths reflected and transmitted with respect to each mirror. These bands are large so that future studies can determine the effect different width bandpass filters have on performance in terms of probability of detection and false-alarms, as well as accuracy in skin color estimation.

Figures 3.19 - 3.21 are the measured mirror responses. The mirrors are measured in the same 45° orientation as they would be in the actual system. The green regions show the spectra that need to be reflected and red regions show the spectra that need to be transmitted by each mirror. The high reflection and transmission efficiencies are

3-17
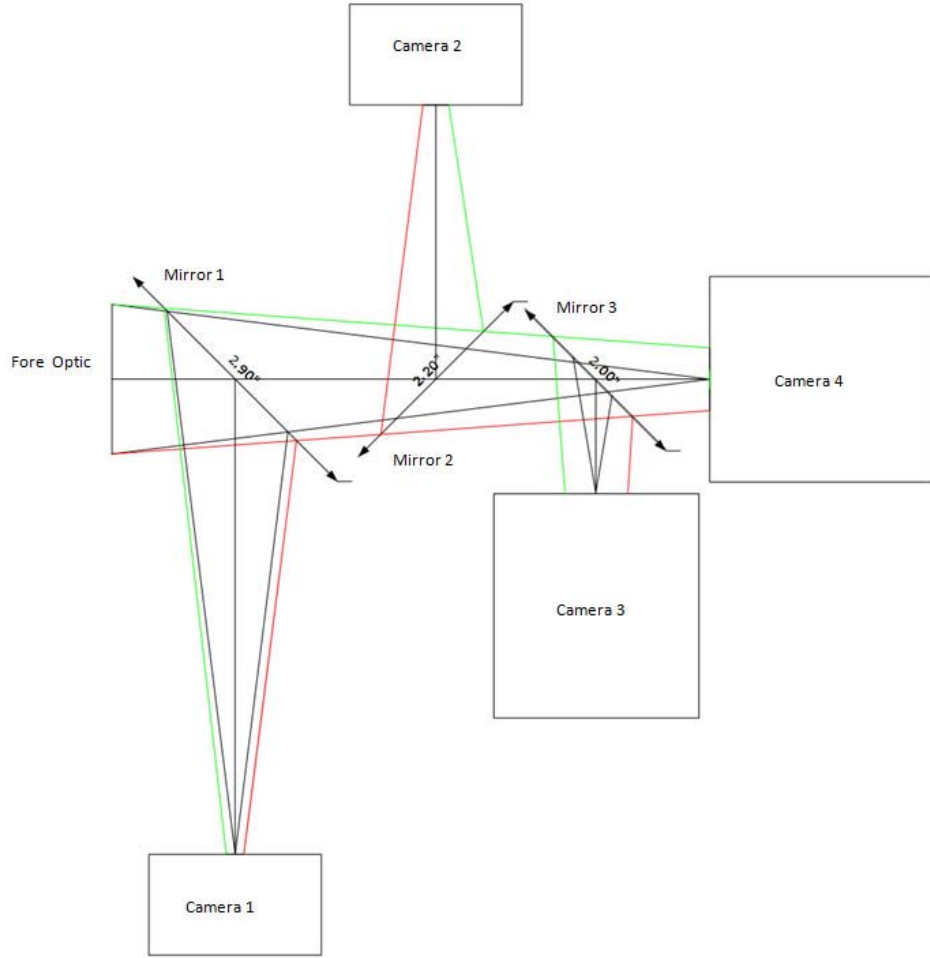
Figure 3.18:   Block diagram of the system with references for the path of the light.

needed to use the skin detection system in low-lighting conditions. It is also important to note that the mirrors are directional with respect to reflected image quality.

3.4   Filters

To reduce the spectral content to those specified in [23], filters are used. The filters need to have high transmission so as not to negate the high percentage of incident energy the mirrors reflect or transmit. The camera used for the 1080nm band has two modes of use. The spectrum it sees can be that reflected by the respective mirror or the mirror and a filter (a Semrock FF01-1060/13-25). The Semrock FF01-1060/13-25 filter has a transmission of >90% for 13nm centered around 1060nm, as

Table 3.8:   Wavelength transmission and reflection bands for mirrors 1, 2, and 3 shown in Fig. 3.1. CW is the center wavelength of the band .

Mirror	Reflected			Transmitted		
	Total (nm)	CW (nm)	Bandwidth (nm)	Total (nm)	CW (nm)	Bandwidth (nm)
1	425-675	550	250	All Other Wavelengths		
2	775-825	800	50	All Other Wavelengths		
3	1030-1130	1080	100	1525-1625	1575	100
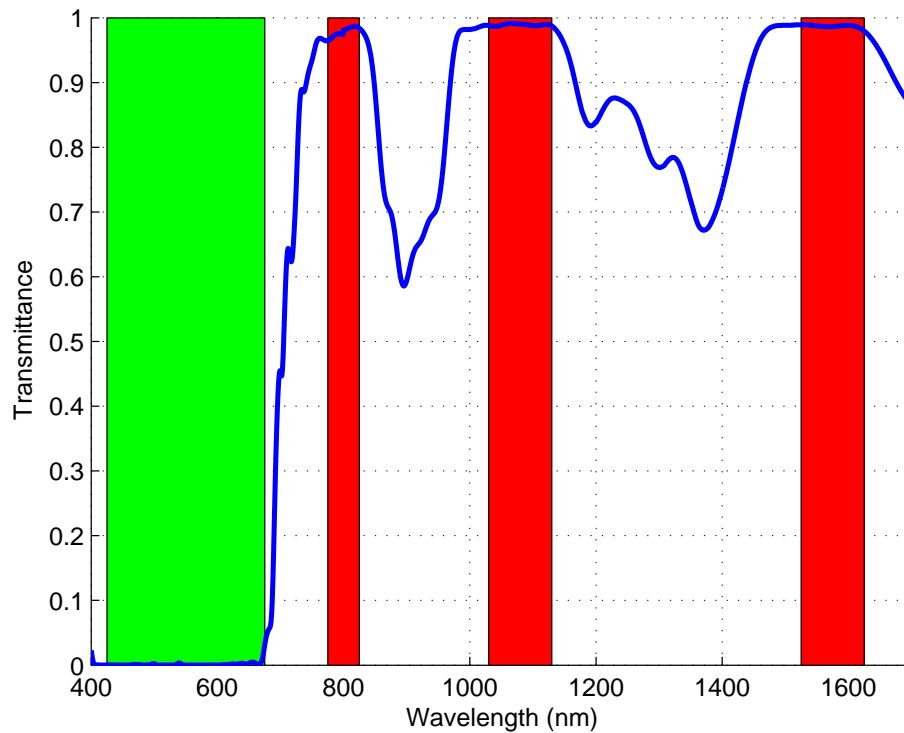
Figure 3.19:   Measured transmittance for Mirror 1. Green represents the relevant reflected spectra and red represents the relevant transmission spectra for the skin detection, melanin estimation, and false-alarm suppression tasks. The mirrors are measured in the same 45° orientation as they would be in the actual system.

shown in Fig. 3.22. The filter needs to work in conjunction with the mirror, because it transmits wavelengths that are not useful in detection. The camera used for the 1580nm band has three reasonable configurations; no filter, a Semrock bandpass filter (NIR01-1570/3-25), or a Reynard longwave pass filter (R01718-00). The Semrock
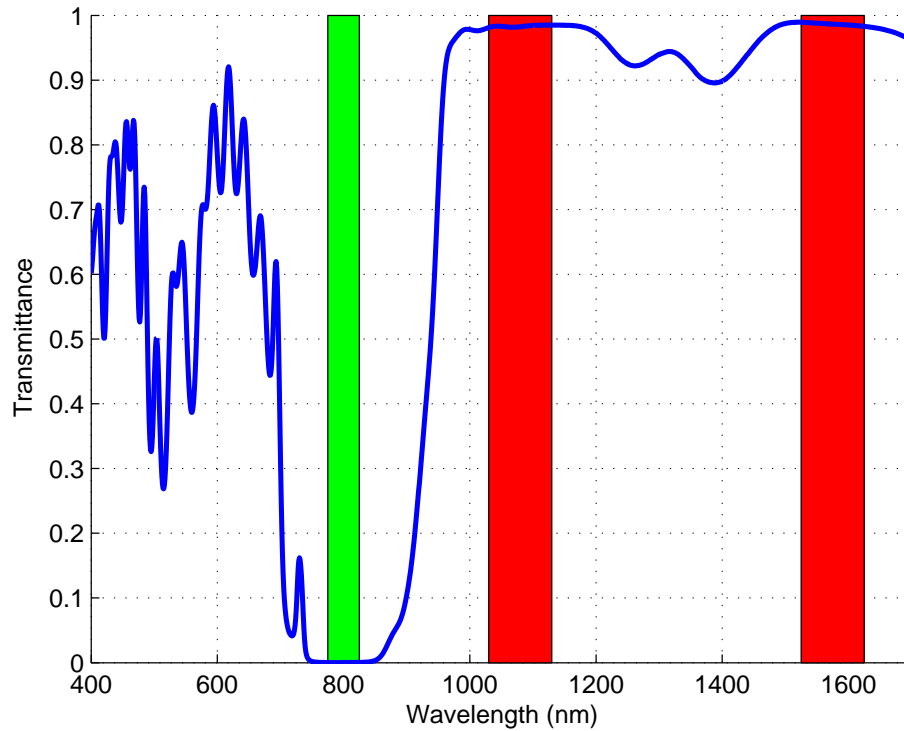
Figure 3.20:   Measured transmittance for Mirror 2. Green represents the relevant reflected spectra and red represents the relevant transmission spectra for the skin detection, melanin estimation, and false-alarm suppression tasks. The mirrors are measured in the same 45° orientation as they would be in the actual system.

NIR01-1570/3-25 filter has a transmission of >90% for 3nm centered around 1570nm, as shown in Fig. 3.23. This filter may not allow enough energy for use in low-light conditions. The Reynard longwave pass filter turns on at 1500nm, as shown in Fig. 3.24, and continues to transmit at high levels far past what is necessary. The downside to this filter is that it might let in too much energy and affect the difference between the 1080nm and 1580nm negatively. A tradeoff analysis is accomplished in Chapter IV to determine which filter works best in the skin detection system.

3.5   Radiometric Model

The purpose of the model is to determine the number of photons that produce electrons at a single pixel for each camera. The number of photons is directly related
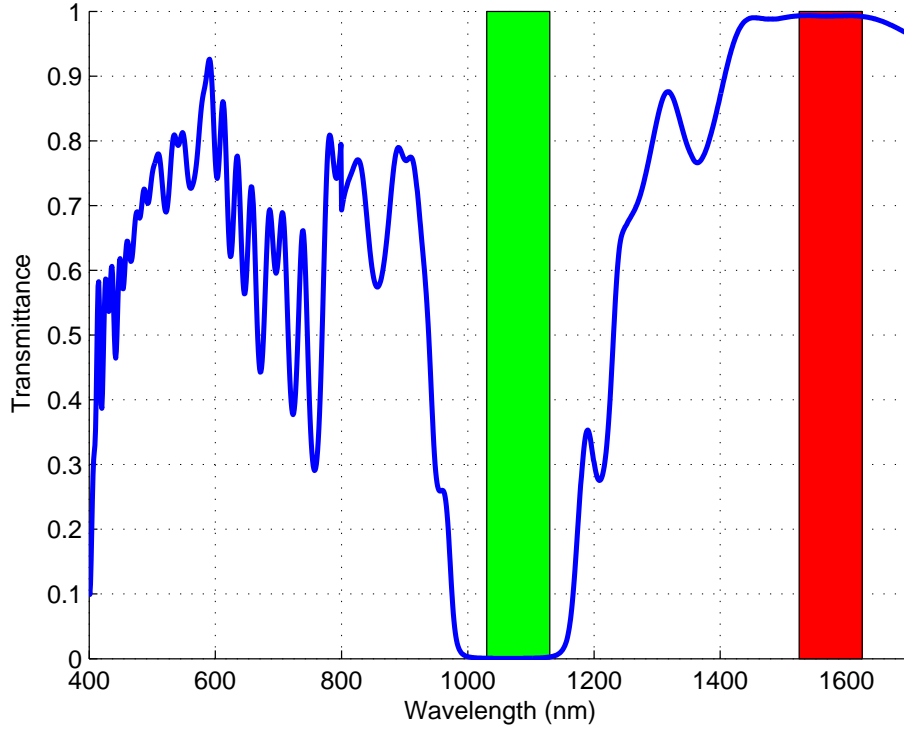
Figure 3.21:   Measured transmittance for Mirror 3. Green represents the relevant reflected spectra and red represents the relevant transmission spectra for the skin detection, melanin estimation, and false-alarm suppression tasks. The mirrors are measured in the same 45° orientation as they would be in the actual system.

to the numbers that an application such as $MATLAB^{®}$ would use to display an image. Because a normalized difference is used to perform the detections, the photon count can be compared in the same way to see if a detection is made. Different target reflections are easily incorporated into the model to simulate plants, snow, or other objects of interest. This is useful in determining detector thresholds giving the best balance between high detections and low false-alarms.

3.5.1 Indoor Scenario Radiometry.   The indoor model is used to test a shorter range scenario where the amount of light incident on the target is easily controlled. Figure 3.25 shows the test layout where $\Theta_d = 15°$, $R_{lamptotarget} = 20$ft, and $R_{targettolens} = 31$ft. All the components are on the same plane in the z-direction

3-21
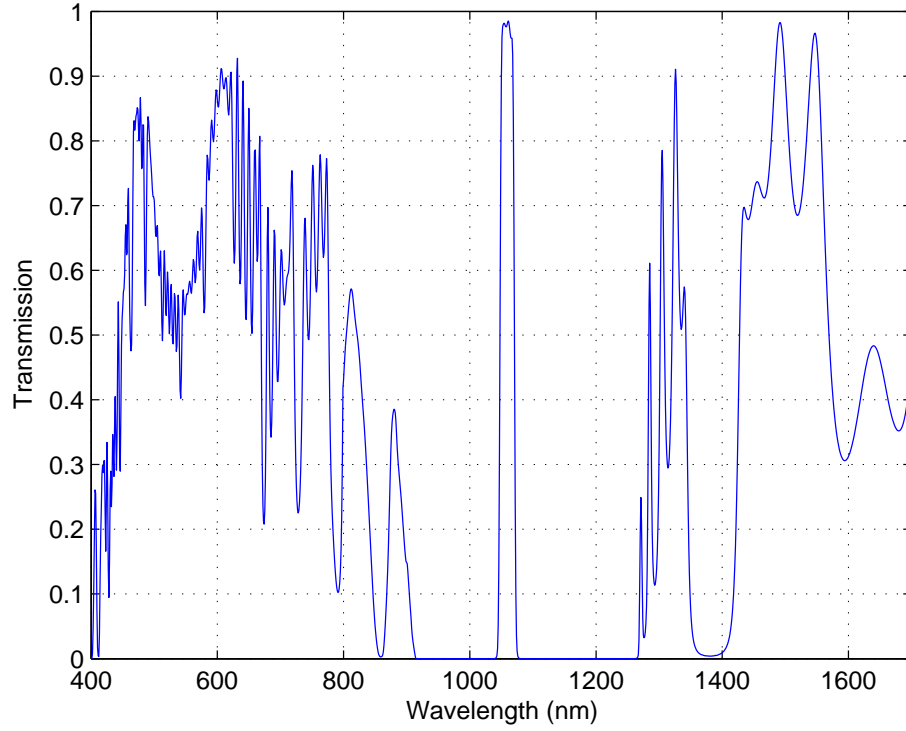
Figure 3.22:   Measured transmission of the Semrock FF01-1060/13-25 NIR band-
pass filter at normal incidence.

except for Lamp 3 in which Θ_d is a depression angle. The three illumination sources
in Fig. 3.25 are Analytical Spectral Devices (ASD) pro lamps. These lamps have an
adjustable field of view of 13-50 degrees and use a (JCV14.5V-50WC) 50 watt lamp
with a color temperature of 3200° Kelvin [19].

First, the radiance of the lamp is determined using the blackbody formula spec-
ified in Eqn. (2.25) with a temperature of 3200° Kelvin, shown in Fig. 3.26. Next, the
irradiance of the lamps on the target is determined with:

$$
\begin{aligned}
E_e\left[\lambda\right] &= \frac{L_e\left[\lambda\right]\cos\left(\theta_d\right)\cos\left(\theta_s\right)A_s\tau_{\mathrm{atm}}}{R_{\mathrm{lamptotarget}}{}^2} \\
&= \frac{L_e\left[\lambda\right]\cos\left(15°\right)6.54\tau_{\mathrm{atm}}}{609.6^2}
\end{aligned}
\tag{3.1}
$$
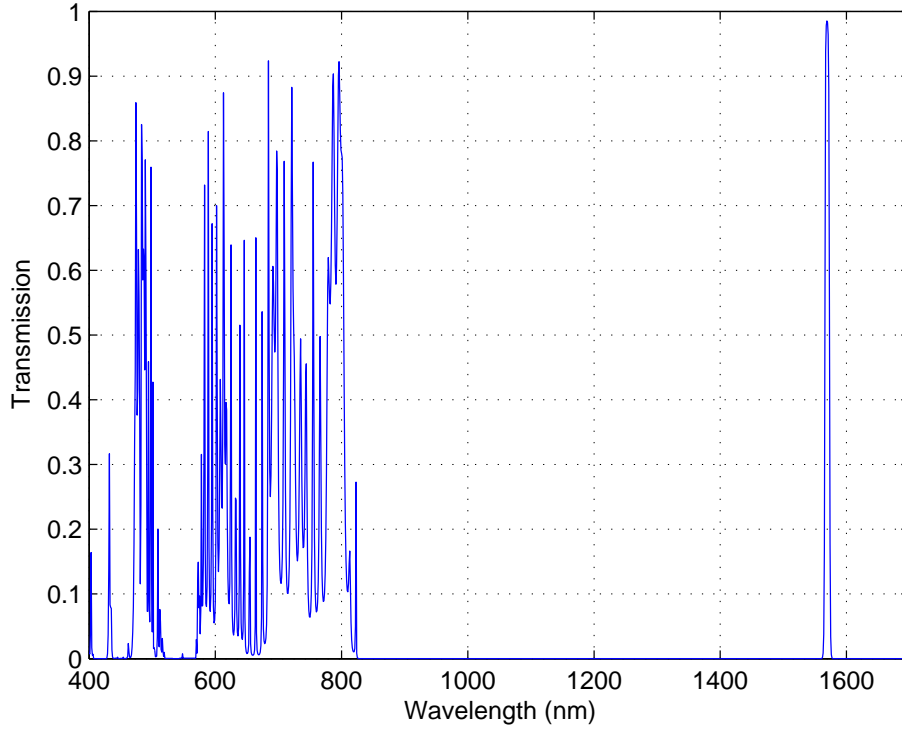
Figure 3.23:   Measured transmission of the Semrock NIR01-1570/3-25 NIR band-
                pass filter at normal incidence.

where $\theta_s = 0°$, $\theta_d = 15°$, (τ_{atm}) is atmospheric transmission curve between the lamps and the target, (A_s) is the effective source area, and $R_{lamptotarget} = 20$ft. (τ_{atm}) is determined using the extinction coefficient discussed in Section 2.5.5. Figure 3.27 shows the atmospheric attenuation for distance of 20ft between the lamp and target. The area of the source A_s is not known but can be determined. Since the power of the light bulb and the FOV of the lamp are known, the flux equation can be rearranged to solve for an effective source area A_s:

$$
\begin{aligned}
A_s &= \frac{\Phi_{\text{bulb}}}{\Omega_{\text{fovbulb}} \int_0^\infty L[\lambda, 3200K]\, d\lambda} \\
&= \frac{50}{0.0403 \times 189.266} \\
&= 6.54 cm^2
\end{aligned}
\tag{3.2}
$$
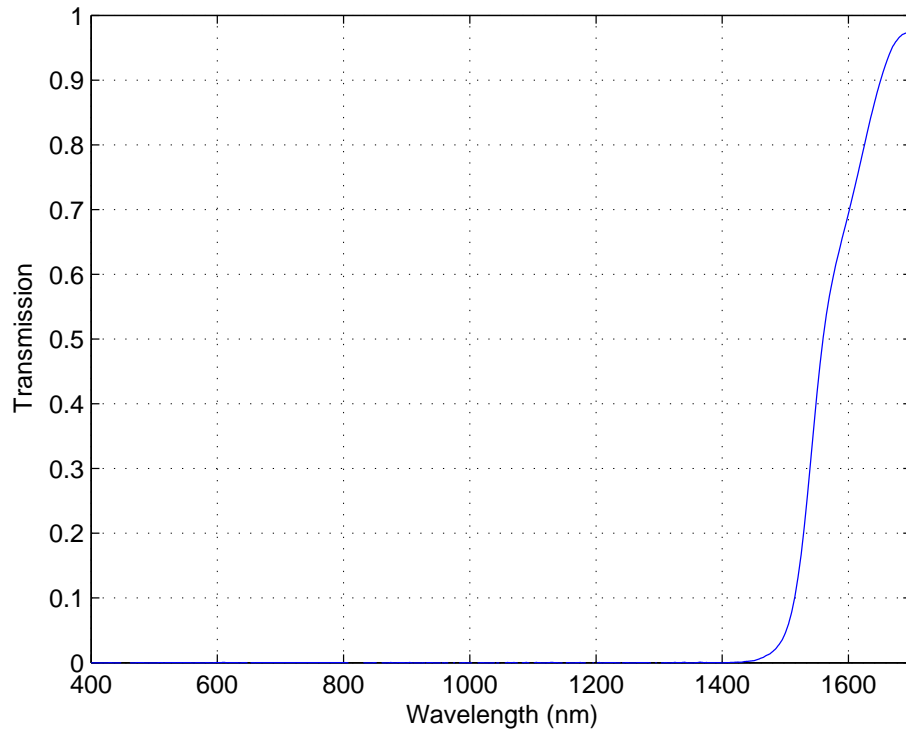
Figure 3.24:   Measured transmission of the Reynard Corporation R01718-00 long wave pass filter at normal incidence.
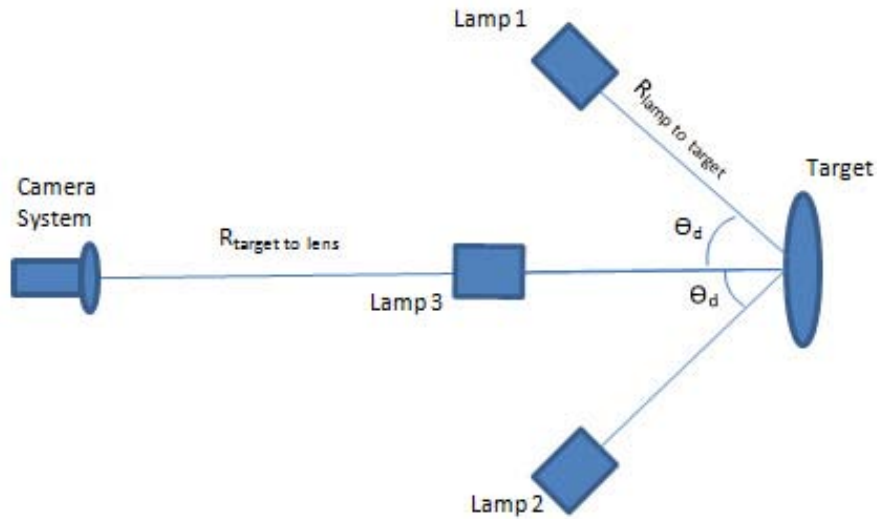
Figure 3.25:   Top down view of the physical indoor setup for system testing where, $\theta_d = 15°$ for each lamp and $R_{targettolens} = 31ft$. Lamp three's θ_d is a depression angle.

3-24
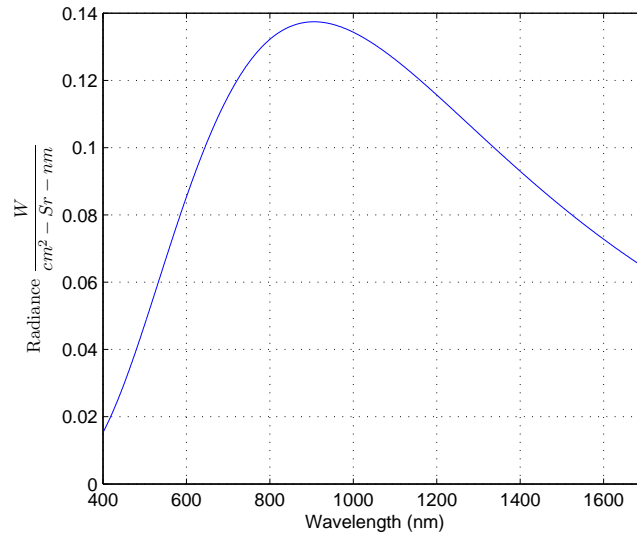
Figure 3.26:   Blackbody radiance curve for a single ASD pro lamp.
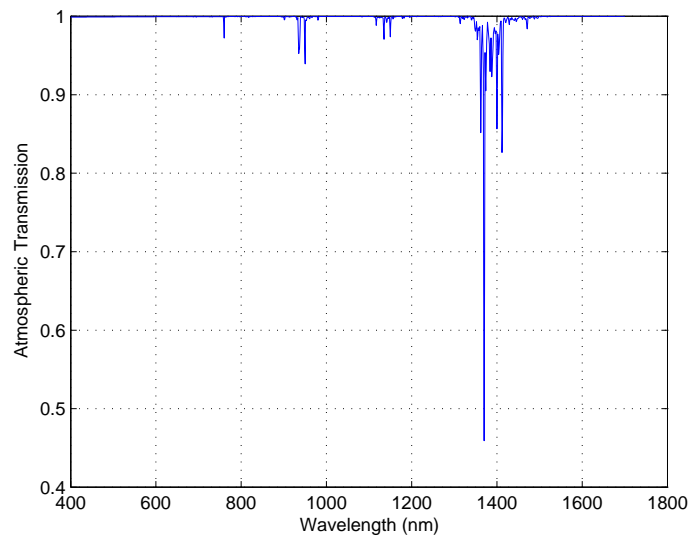
Figure 3.27:   The atmospheric transmission for a 20ft distance between the lamps and target.

where the FOV used in calculating $\Omega_{fovbulb}$ is 13°, which is the ASD Pro Lamp's smallest FOV. The flux of each bulb (Φ_{bulb}) is the light's rated power, 50 W. The resulting irradiance is solved and shown in Fig. 3.28.
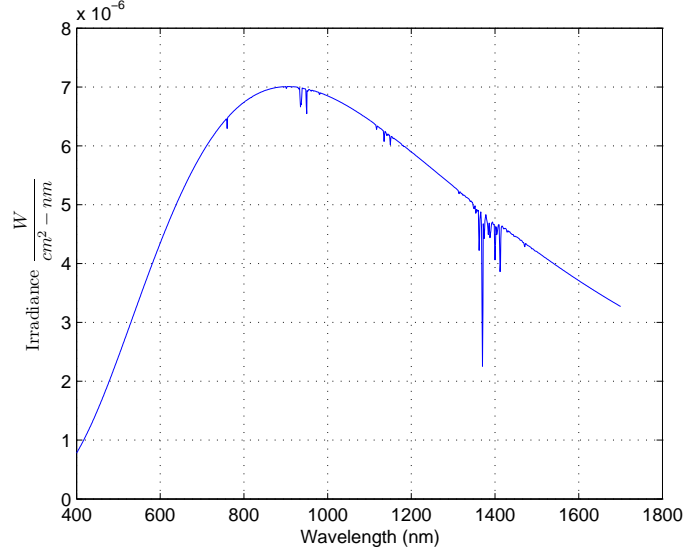
Figure 3.28:   The modeled irradiance on the target from three lamps.

To find the reflected exitance of the target, the irradiance is multiplied by the target reflectance:

$$M_e\left[\lambda\right] = E_e\left[\lambda\right]\rho_{\text{target}}\left[\lambda\right],\tag{3.3}$$

in this case human skin. Because the source is assumed lambertian, determining the radiance is achieved by dividing by π:

$$L_e\left[\lambda\right] = \frac{M_e\left[\lambda\right]}{\pi}.\tag{3.4}$$

(Note that skin is nearly lambertian when the illumination source is perpendicular to the skin. [20]) Figures 3.29 and 3.30 show the spectral exitance and radiance respectively of the target.

3.5.2   Modeling the Physical System.   With the radiance of the target known, the amount of electron forming photons at an individual pixel is:

3-26
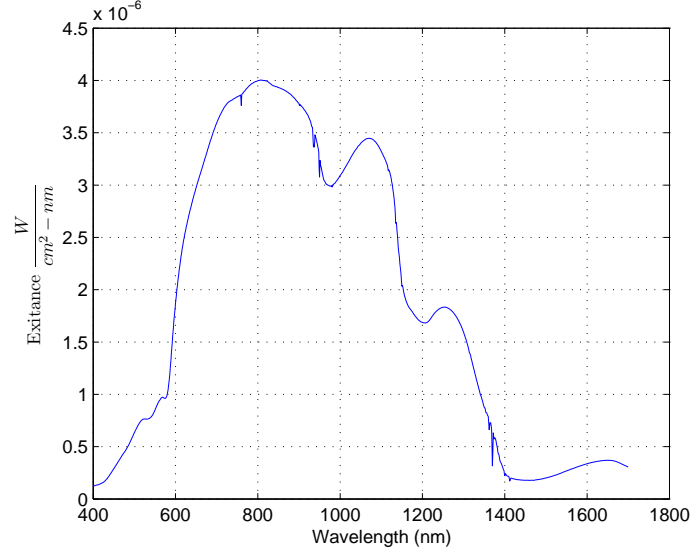
Figure 3.29:　The modeled exitance of the target for TypeI/II skin.
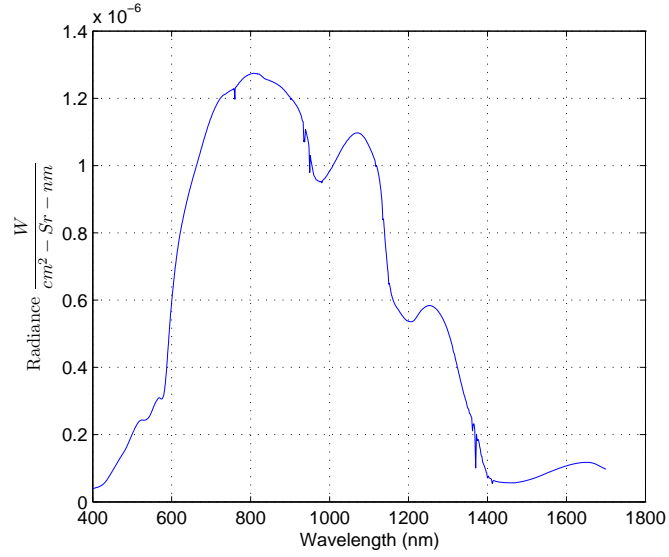
Figure 3.30:　The modeled radiance of the target for TypeI/II skin.

$$\Phi_{p-\text{pixel}} = \int_{400\text{nm}}^{1700\text{nm}} L_{e-\text{target}} \ \Omega_{\text{pixel}} \ A_{\text{opt}} \ \tau_{\text{atm}} \ \tau_{\text{optics}-\text{filters}} \ \frac{\lambda}{hc} \ \tau_{\text{int}} \ \eta \ d\lambda \qquad (3.5)$$

where

3-27

- $L_{e-target}(\lambda)$ is the target's spectral radiance per Eqn. (3.4).

- Ω_{pixel} is the solid angle field of view of the pixel. This is computed by dividing the area of the pixel by the focal length squared of the lens. This distance can be used because objects are far enough away that the image distance is equal to the focal length.

- A_{opt} is the area of the entrance window of the optical system, or in radiometric terms, the area of the detector. This can be used as the detector area, because the amount of energy that is received by the entrance window is the amount incident on the pixel.

- $\tau_{atm}(\lambda)$ is the atmospheric transmission of the path between the target and the front lens of the system.

- $\tau_{optics-filters}(\lambda)$ is the spectral transmission of all the components in the specific optical chain being studied. It is an important variable because it makes the photon count as realistic as possible. In the system designed in the thesis there are four different transmission paths for the light to follow. Table 3.9 shows the objects in each of the four optical paths. Figures 3.31 - 3.34 show the spectral transmission of each path including all filter options.

- The fraction $\lambda/(h\,c)$ converts energy units (Φ_e) to photon units (Φ_p).

- After the conversion above, the units of this system are photons per second, which is where the integration time τ_{int} becomes important. Whatever integration time the physical cameras are set to can be taken into consideration in the model.

- The last step incorporates the quantum efficiency ($\eta(\lambda)$) of each camera as discussed in Section 2.5.6. The spectral quantum efficiency is part of the specifications provided by the vendor [12, 30]. Figures 3.35 and 3.36 show the quantum efficiency of the ThorLabs and Goodrich cameras, respectively.

Equation 3.5 is used for every camera and filter combination to determine the anticipated number of electron-forming photons. The results are shown in Chap-

3-28

Table 3.9:   The optical component order (OCO) for each camera's optical path including filter options. The attenuation of the incident light is calculated with these objects in mind. (R) represents reflection off mirror while (T) represents transmitting through.

OCO	Camera 1	Camera 2	Camera 3	Camera 4
1	Fore Optic	Fore Optic	Fore Optic	Fore Optic
2	Mirror 1(R)	Mirror 1(T)	Mirror 1(T)	Mirror 1(T)
3	Lens 1	Mirror 2(R)	Mirror 2(T)	Mirror 2(T)
4	IR cut filter	Lens 2	Mirror 3(R)	Mirror 3(T)
5	RGB array filter		No Filter	No Filter
5			or Bandpass Filter	or Bandpass Filter
5				or Longwave Pass Filter
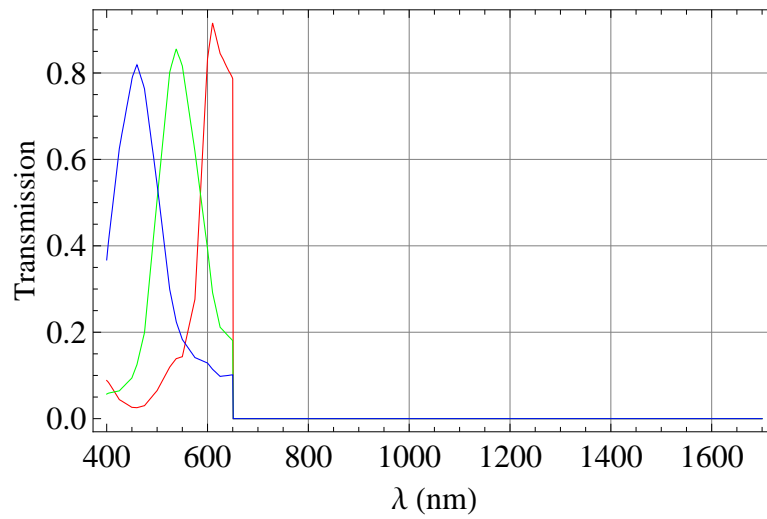
Figure 3.31:   Spectral transmittance of all objects in the path of *Camera 1* including the camera's spectral response. The red, green, and blue curves represent the amount of transmittance for each color channel.

ter IV. The empirical line method is performed on these numbers to change them to estimated reflectance. Labsphere *Spectralon*® panel measurements are used as the known reflectance. The ELM equation [Eqn. (2.1)] is simplified and rewritten to represent the case where both dark and light panels are available:

$$\hat{\rho} = \frac{P * \rho_{\text{gray}} - P_{\text{white}} * \rho_{\text{gray}} - P * \rho_{\text{white}} + P_{\text{gray}} * \rho_{\text{white}}}{P_{\text{gray}} - P_{\text{white}}} \tag{3.6}$$
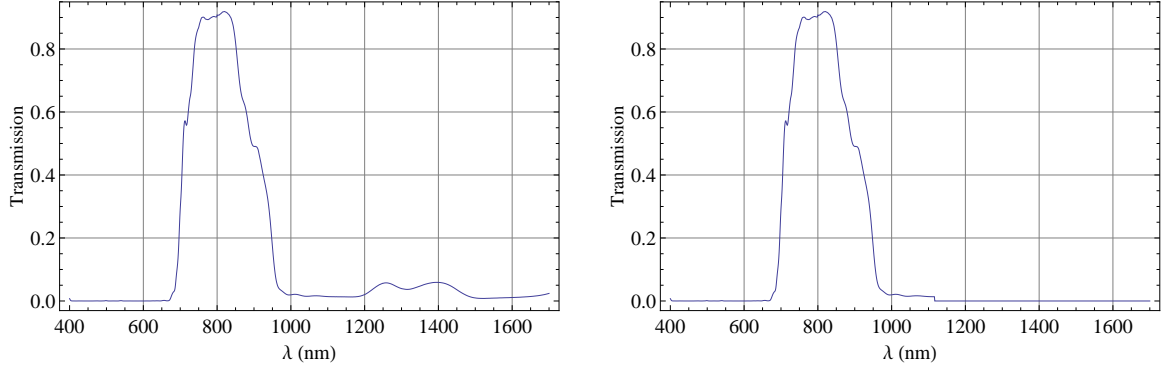
Figure 3.32: (Left) Spectral transmittance of all objects in the path of *Camera 2* not including the camera's spectral response. (Right) Spectral transmittance of all objects in the path of *Camera 2* including camera's spectral response. The response is modeled at a value of 1 until the cutoff wavelength of 1116nm where it is a value of 0.
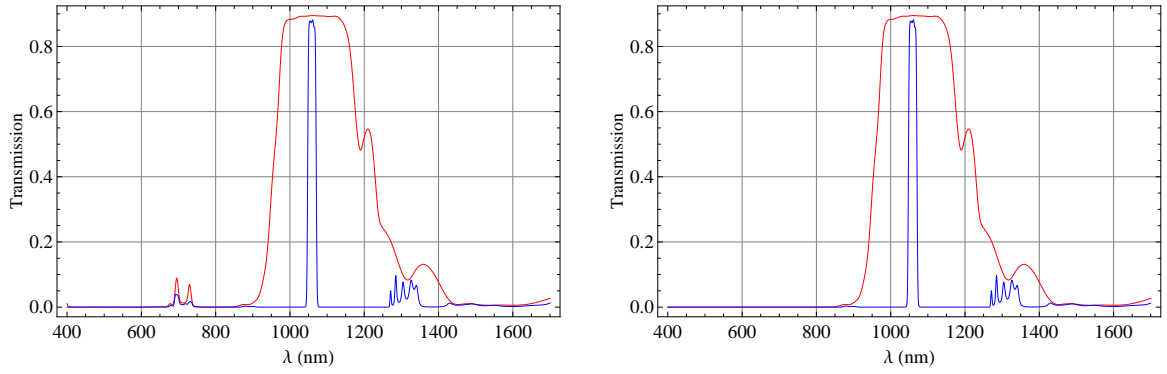
Figure 3.33: (Left) Spectral transmittance of all objects in the path of *Camera 3* not including the camera's spectral response. (Right) Spectral transmittance of all objects in the path of *Camera 3* including camera's spectral response. The response is modeled at a value of 0 until the cut on wavelength of 800nm where it is a value of 1. The red curve shows the configuration without additional filtering while the blue adds the Semrock bandpass filter.

where

- P is the photon count for each camera for the material being estimated (skin, vegetation, etc).

- ρ_{white} is the reflectance of the white panel. This value is calculated by using a weighted average of the panel's reflectance shown in Fig 3.37. The panel's reflectance is weighted by the system transmissions, including camera response,

3-30
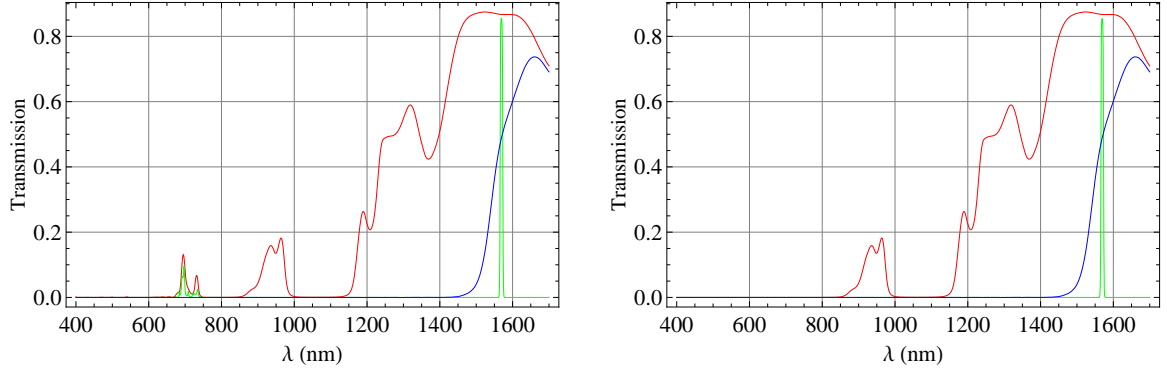
Figure 3.34: (Left) Spectral transmittance of all objects in the path of *Camera 4* not including the camera's spectral response. (Right) Spectral transmittance of all objects in the path of *Camera 4* including camera's spectral response. The response is modeled at a value of 0 until the cut on wavelength of 800nm where it is a value of 1. The red curve shows the configuration without additional filtering, the green curve adds just the Semrock bandpass filter, and the blue curves adds just the Reynard longwave pass filter.
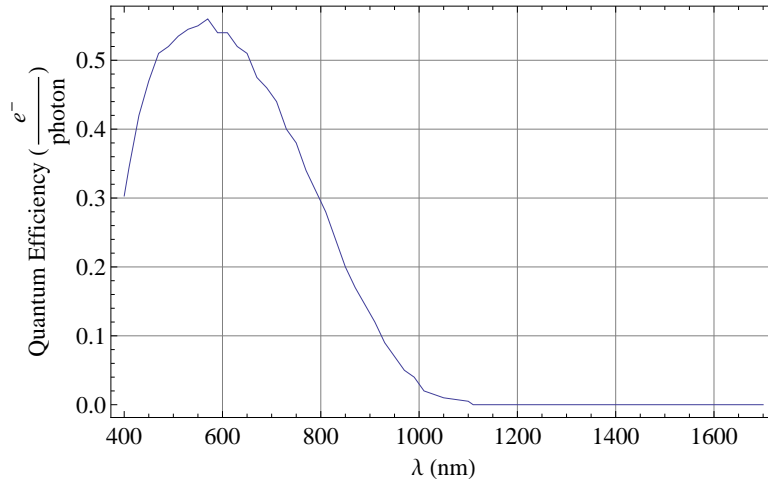
Figure 3.35: Quantum efficiency of the ThorLabs silicon focal plane array.

shown in Fig. 3.31 - 3.34. Table 3.10 shows the calculated values for every system configuration.

- ρ_{gray} is the reflectance of the gray panel. This value is calculated by using a weighted average of the panel's reflectance shown in Fig 3.38. The panel's reflectance is weighted by the system transmissions, including camera response,

3-31
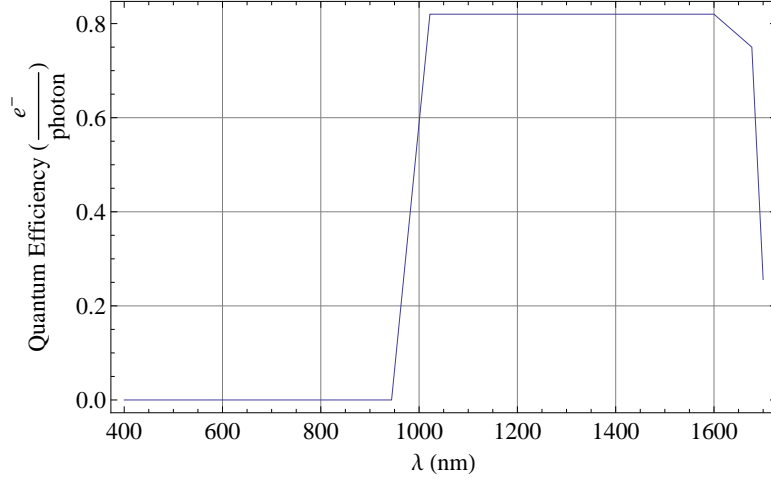
Figure 3.36: Quantum efficiency of the Goodrich InGaAs focal plane array.
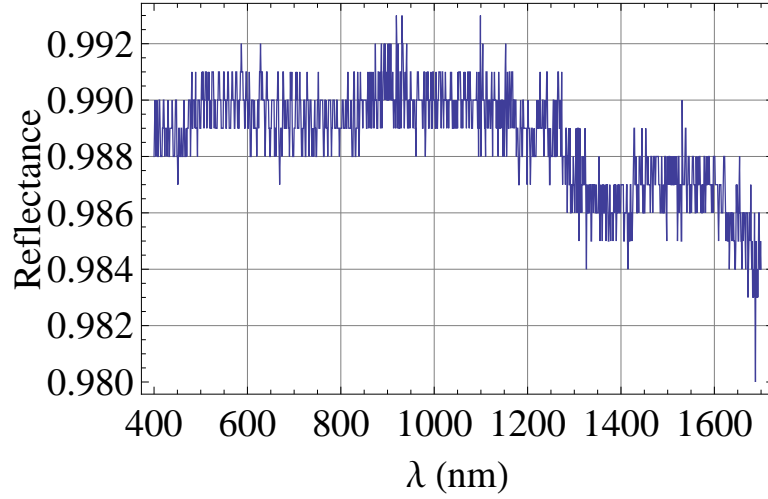
Figure 3.37: Reflectance of the white Labsphere $Spectralon^{®}$ panel.

shown in Fig. 3.31 - 3.34. Table 3.10 shows the calculated values for every system configuration.

- P_{white} is the number of electron creating photons when the white panel is the target, and is determined using Eqn. (3.5).

- P_{gray} is the number of electron creating photons when the gray panel is the target, and is determined using Eqn. (3.5).

3-32
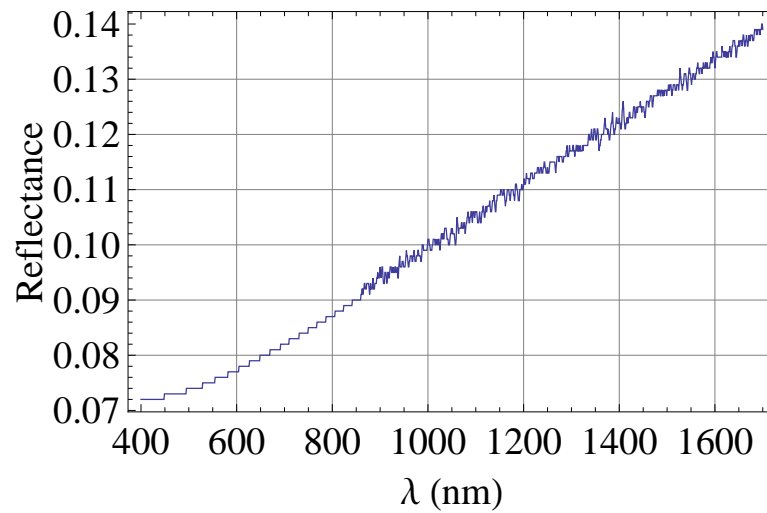
Figure 3.38:   Reflectance of the gray Labsphere *Spectralon*® panel.

3.6   Summary

Each component in the system is discussed including the detectors, lenses, dichroic mirrors, and filters. The discussion describes each component and also characterizes it. The second half of this chapter discusses how each of these components fits into the radiometric model of the system. With the components chosen and system and model completed the results of each can be analyzed.

Table 3.10: Table showing the reflectance values that should be estimated. These values are based on the measured skin reflectance weighted by the system transmission for each camera's optical chain.

	Averaged Reflectance Value	
Configuration	White Panel	Gray Panel
Camera 1 Red Channel	0.9897	0.0772
Camera 1 Blue Channel	0.9893	0.0735
Camera 1 Green Channel	0.9898	0.0752
Camera 2	0.9894	0.0911
Camera 3 No Filtering	0.9895	0.1058
Camera 3 with Semrock FF01-1060/13-25	0.9895	0.1064
Camera 4 No Filtering	0.9895	0.1257
Camera 4 with Semrock NIR01-1570/3-25	0.9870	0.1317
Camera 4 with Reynard R01718-00	0.9871	0.1348
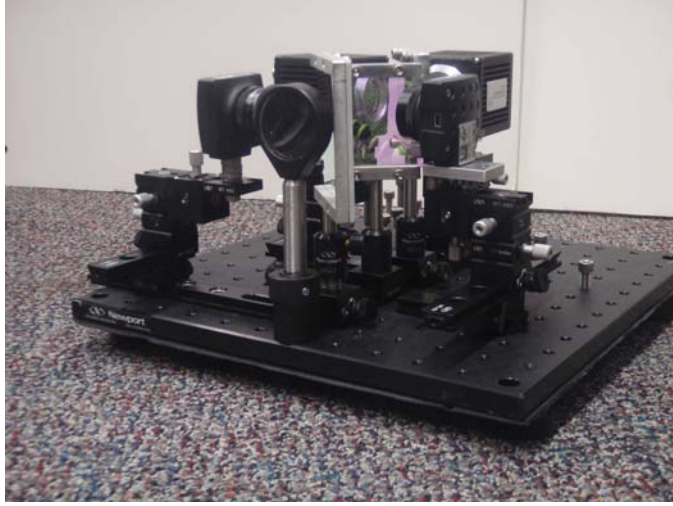
Figure 4.1:   Picture of the skin detection, melanin estimation, and false-alarm suppression system designed and implemented in this thesis.

IV. Results and Analysis

This chapter shows the output of the designed system, discusses the problems encountered, and how these problems are overcome. The model's two outputs, photon count and estimated reflectance, are shown and discussed. A comparison is made to show how close the model and system's estimated reflectance values are to the measured skin reflectance of the target, and compares to the reflectance of skin in imagery from [23].

4.1   Qualitative Analysis

A photo of the optical system designed, analyzed, and built in this thesis is shown in Fig. 4.1. To ensure minimal stray light, a cover is made to go over the entire system leaving only the fore optic exposed. The image quality of each camera is discussed and a description of how low-image-quality issues are resolved is provided.

4.1.1   Visual Assessment of Image Quality.   Images are acquired from all four cameras and visually inspected for quality. As shown in Fig. 4.2 (Left), the quality of the red, green, and blue camera (*Camera 1*) is poor even after adjusting the focus and integration time in an attempt to improve image quality. (An image

Figure 4.2:   (Left) Image showing the highest visible quality image possible from *Camera 1* by adjusting the focus and integration time. (Right) Image showing the highest quality image possible from *Camera 3* by adjusting the focus and integration time. Note that focus decreases from left to right in the image.

from *Camera 2*, not shown, experiences the same effects.) To determine the source of the poor image quality, the optical chain of *Camera 1* is reassembled one component at a time. The process of discovering the source of the problem and implementing a solution is discussed in Section 4.1.2. *Camera 3* and *Camera 4* also show poor image quality. Figure 4.2 (Right) shows the highest-quality image attained from *Camera 3* by adjusting the focus and integration time. The poor quality is seen in comparing the focus of the left and right sides of the image. (An image from *Camera 4* is not shown, but the same effects are seen.) Section 4.1.3 discusses the cause of the selective focus problem and how it is resolved.

4.1.2   Addressing Image Quality Issues for Camera 1 and Camera 2.   First, the orientation of the achromatic doublet lens is checked, then an image is taken with just the fore optic and the ThorLabs DCC1645C camera, the result of which is shown in Fig. 4.3 (Left). As seen, the image comes to a crisp focus, demonstrating that the image quality issue is not caused by these components. Next, *Lens 2* is added to the chain of *Camera 1* and the image quality decreases, as seen in Fig. 4.3 (Right). The effect seen (bright center, getting radially dimmer) is most likely vignetting.

Figure 4.3: (Left) Image acquired with the fore optic and ThorLabs DCC1645C (*Camera 1*). Note the image quality in terms of focus improved compared to Fig. 4.2. Issues with color seen are due to auto coloring and gaining aspects from the manufacturer's software. (Right) Image acquired with the fore optic, second lens (*Lens 1*), and the ThorLabs DCC1645C *Camera 1*, where decreased image quality is seen.

Vignetting is defined as a clipping or truncation of the off-axis ray bundles by elements distant from the aperture stop [9]. To solve this problem, an iris diaphragm is placed directly in front of *Lens 2* attached to *Camera 1*. The image shown in Fig 4.4 (Left) has the diaphragm closed down to 8.3mm. The quality is greatly improved by this addition, which indicates that vignetting is a issue. (The darkness around the top of the image is due to a misalignment of the iris diaphragm relative to the center of the lens. This issue is currently resolved and new images will be used in the final thesis.) The last step is to insert the mirror into the optical chain, moving *Camera 1* to its original position. Figure 4.4 (Right) shows an image taken with all of the elements in *Camera 1's* optical chain. (The slight out of focus issue is caused by the iris diaphragm not being centered on the lens, as seen in the image, but is currently resolved.) Compared to the image seen in Fig. 4.3 (Right), there is a large improvement in image quality due to the use of the iris diaphragm. Since the same effects are seen in *Camera 2*, an iris diaphragm is added to correct for its poor image quality. Fig. 4.5 (Left) and Fig. 4.5 (Right) demonstrate the image quality of *Camera 1* and *Camera 2* obtained by adding the iris diaphragms, respectively.

Figure 4.4:   (Left) Image acquired with the fore optic, second lens (*Lens 1*), iris diaphragm, and the ThorLabs DCC1645C (*Camera 1*). The iris diaphragm is closed down to 8.3mm. (Right) Image acquired with the fore optic, second lens (*Lens 1*), iris diaphragm, *Mirror 1*, and the ThorLabs DCC1645C (*Camera 1*). Some reduction in image quality is seen due to the iris diaphragm not being centered perfectly on the lens.

Table 4.1:   Camera settings used to acquire the images shown in Fig. 4.5 (Left,Right) and 4.6 (Left, Right).

Camera	Integration Time (ms)	Gain	Filter	Diaphragm Diameter (mm)
1	66.669	6	N/A	5.45
2	71.556	1	N/A	4.35
3	10.58	2	Semrock FF01-1060/13-25	N/A
4	18.77	2	Semrock NIR01-1570/3-25	N/A

4.1.3 Addressing Image Quality Issues for Camera 3 and Camera 4.   The effect seen in *Camera 3* and *Camera 4* is a result of the Scheimpflug principle [26]. This is where the lens plane is not parallel to the image plane and results in selective focus. In the case of this specific system, the mirrors can contribute to this effect by not being aligned to 45°. To alleviate this issue, a compass is used to make sure each mirror is as close to 45° as possible. The fore optic and cameras are adjusted to make sure proper alignment is maintained and that they are not rotated in any direction.

Figure 4.5:   (Left) Raw image from the ThorLabs DCC1645C used for NDGRI calculation (*Camera 1*).   (Right) Raw image from the ThorLabs DCC1545M used for melanin estimation (*Camera 2*).

Figure 4.6:   (Left) Raw image from the Goodrich SU640KTSX-1.7RT used for skin detection (*Camera 3*) using the Semrock FF01-1060/13-25 filter. This configuration results in the light transmitting to (*Camera 3*) as shown in Fig 3.33 (blue curve). (Right) Raw image from the Goodrich SU640KTSX-1.7RT used for skin detection (*Camera 4*) using the Semrock NIR01-1570/3-25. This configuration results in the light transmitting to the (*Camera 4*) as shown in Fig 3.34 (green curve).

The images shown in Fig. 4.6 show the highest visual quality images available after the mirrors, cameras, and lens positions are checked.

Table 4.2:   Expected skin reflectance values generated by applying the transmission curves of Fig. 4.7 (Right) to the skin reflectance in Fig. 4.7 (Left) used in comparing the model and the optical system.

Camera Configuration	Reflectance Value
Camera 1 Green Channel	0.291
Camera 1 Red Channel	0.427
Camera 2	0.544
Camera 3 with Semrock FF01-1060/13-25	0.452
Camera 4 with Semrock NIR01-1570/3-25	0.077

4.2   Quantitative Analysis

To collect data for the indoor scenario, the setup discussed in Section 3.5.1 is used. Images are acquired with a person, reflectance panels, and snow in the scene. (The snow is common confuser due to its high scattering and water absorption properties [23].) The use of three lamps is to attempt to achieve uniform illumination. The camera parameters used to acquire the images are shown in Table 4.1. The test setup and camera parameters apply to Fig. 4.5 and Fig. 4.6, which are the raw images used in the analysis of the system. Here, the raw images are converted to estimated reflectance using empirical line method (ELM). The reflectance estimated by the model and the optical system developed in this thesis are compared to the actual reflectance of human skin. The measured reflectance of the target used in this comparison is shown in Fig. 4.7 (Left). Since the cameras are receiving broad spectral bands of light, the true reflectance is not the reflectance at the center wavelength for the given band. The actual reflectance value is a result of integrating across the bands of the measured skin reflectance spectrally taking the system transmission from each camera's optical chain into consideration (Fig. 4.7) (Right). These computed values are reported in Table 4.2.

4.2.1   Comparing Estimated Reflectance From the Physical System to Measured Reflectance.
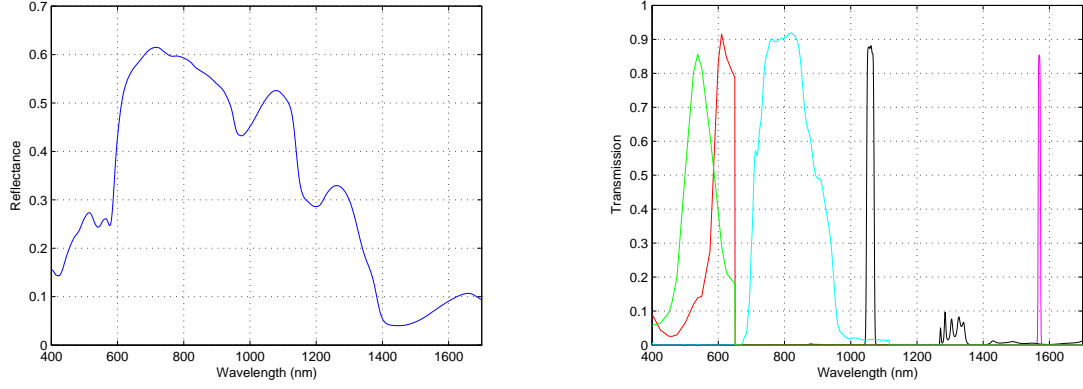
Figure 4.7:   (Left) Diffuse skin reflectance spectra obtained with a hand-held reflec-
tometer, of the test subject used in validating the optical system and
model. (Right) The transmissions used in the weighted average of the
skin reflectance. The red and green curves represent the RGB camera
channel received spectra. The cyan curve represents *Camera 2's*, black
represents *Camera 3's*, and maroon represents *Camera 4's* transmission
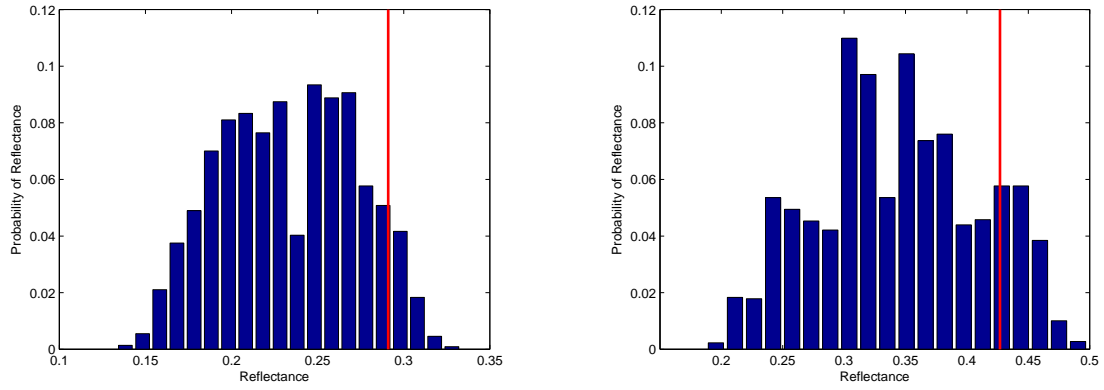
Figure 4.8:   (Left) Distribution of 2184 neck pixels for the green channel of *Cam-
era 1.* (Right) Distribution of 2184 neck pixels for the red channel
of *Camera 1.* The red line shows where the expected diffuse skin re-
flectance is located, per Table 4.2.

4.2.1.1 Camera 1. To determine how close the estimations are to the
expected values shown in Table 4.2, the pixels across the target's neck are used. Fig-
ure 4.8 (Left) shows the distribution of the skin reflectance values for 2184 neck pixels
for the green channel of *Camera 1.* Similarly, Fig. 4.8 (Right) shows the distribution
of the skin reflectance values for 2184 neck pixels for red channel of *Camera 1.* The
red lines show the locations of the expected diffuse reflectance, per Table 4.2.

Figure 4.9:   Estimated reflectance from *Camera 2* using the raw data shown in Fig. 4.5 (Right).

4.2.1.2   Camera 2.   The estimated reflectance of Fig. 4.5 (Right) is shown in Fig. 4.9. To see how close the estimations are to the expected values shown in Table 4.2, a group of neck pixels is used. Figure 4.10 shows the distribution of the skin reflectance values for 1960 neck pixels for *Camera 2*. The expected value is right on the mode of the collected data. This shows the estimation for *Camera 2* is as expected.

4.2.1.3   Cameras 3 and 4.   The estimated reflectance for *Camera 3* and *Camera 4* are shown Fig. 4.11 (Left) and 4.11 (Right) respectively. Figure 4.12 (Left) shows the distribution of the skin reflectance values for 2184 neck pixels for *Camera 3*. Figure 4.12 (Right) shows the distribution of the skin reflectance values for 2184 neck pixels for *Camera 4*. The red line shows where the expected diffuse reflectance is located. The estimated reflectance values are near the expected reflectance values for both *Camera 3* and *Camera 4*.

4.2.1.4   Comparing Estimated Reflectance From the Physical System to a Hyperspectral Imager.   Using images collected from the HyperSpecTIR 3 (HST3),
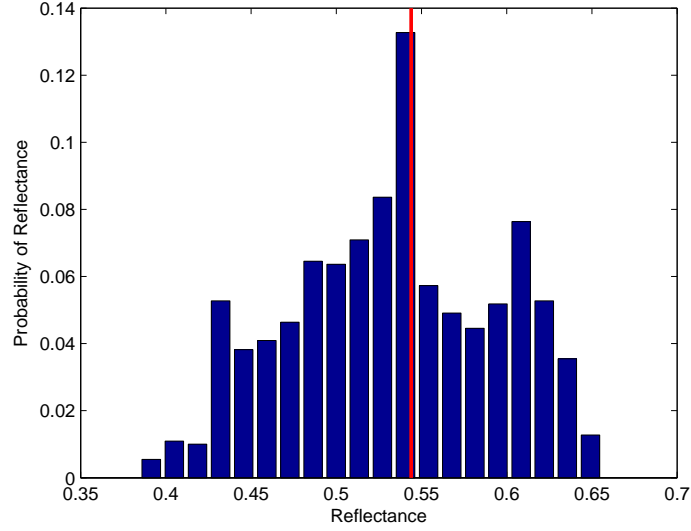
Figure 4.10:   Distribution of 1960 neck pixels for *Camera 2*. The red line shows where the expected diffuse skin reflectance is located, per Table 4.2.
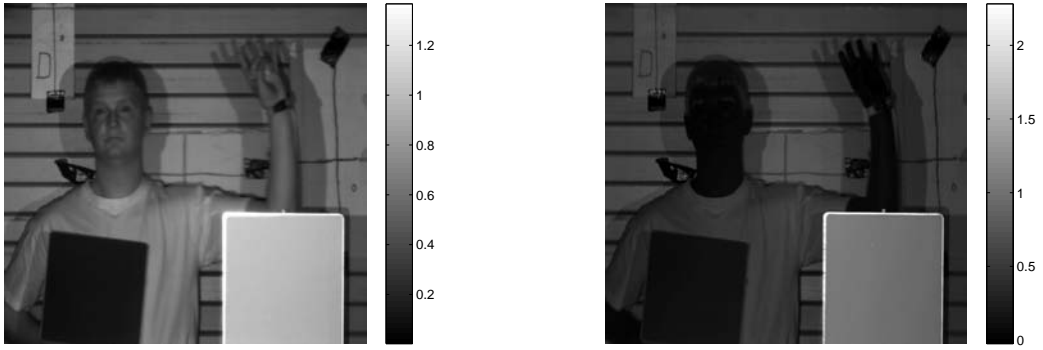
Figure 4.11:   (Left) Estimated reflectance from *Camera 3* using the raw data shown in Fig. 4.6. (Left) Estimated reflectance from *Camera 4* using the raw data shown in Fig. 4.6 (Right).

the same estimated reflectance-based analysis is performed. The HST3 is an imaging system with different noise characteristics, using two different detectors. Also, the scene imaged has different targets and different illumination than the images taken by the designed system. The expectation is that the distributions from these images will be the same. A color image of the test scene is shown in Fig. 4.13 (Top). Since the test images acquired for testing the skin detection system developed in this thesis
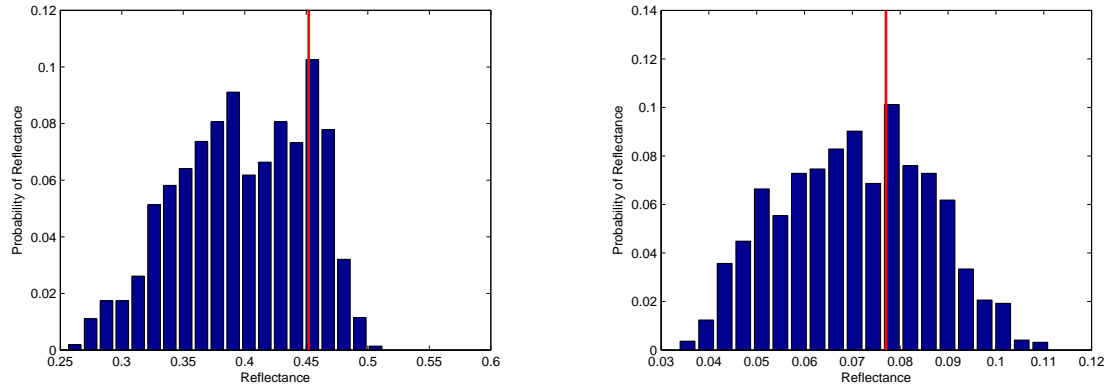
Figure 4.12: (Left) Distribution of 2184 neck pixels for *Camera 3*. (Right) Distribution of 2184 neck pixels for *Camera 4*. The red line shows where the expected diffuse skin reflectance is located, per Table 4.2.

Figure 4.13: (Top) Image acquired by HST3 used for comparison against the skin detection system data. (Bottom) Masked version of the image showing only Type I/II skin used in the analysis.

only have a Type I/II skin target, a mask is used on the HST3 image so only the same skin types are analyzed. The masked image is shown Fig. 4.13 (Bottom).

Since the system under test aggregates different portions of the spectrum than the HST3 is capable of, we choose image bands in the HST3 imager as close to those in the test system. The HST3 bands used for each portion of the spectrum are chosen as:

- Red and green channels are converted to the XYZ colorspace defined by the international commission on illumination, then to the RGB color space as accomplished in [23]

- To estimate melanin bands, the mean of the 18 HST3 bins with centers from 707.402nm to 907.557nm is used.

- The 1060nm Semrock bandpass filter uses the ∼8nm wide bin with a center at 1061.7nm.

- The 1570nm Semrock bandpass filter uses the ∼8nm wide bin with a center at 1570.83nm.

With the bands described above, the distributions shown in Fig. 4.14 - 4.16 are created. The red line shows where the expected diffuse skin reflectance is located, per Table 4.2. Figure 4.14 shows the distribution for the red channel (Left) and green channel (Right) of the HST3 image. Figure 4.15 shows the distribution for the melanin estimation channel of the HST3 image. Figure 4.16 shows the distribution for the filtered 1060nm channel (Left) and filtered 1570nm channel (Right) of the HST3 image.

A visual inspection of both the HST3 and designed camera system's histograms indicates that they have similar shape. A more accurate comparison would be to compute the similarity of both sets of distributions with a formal metric. This is accomplished using the Bhattacharyya coefficient (BC). The BC is calculated by segmenting each distribution into an arbitrary number of bins based on their values and then computing the coefficient as:
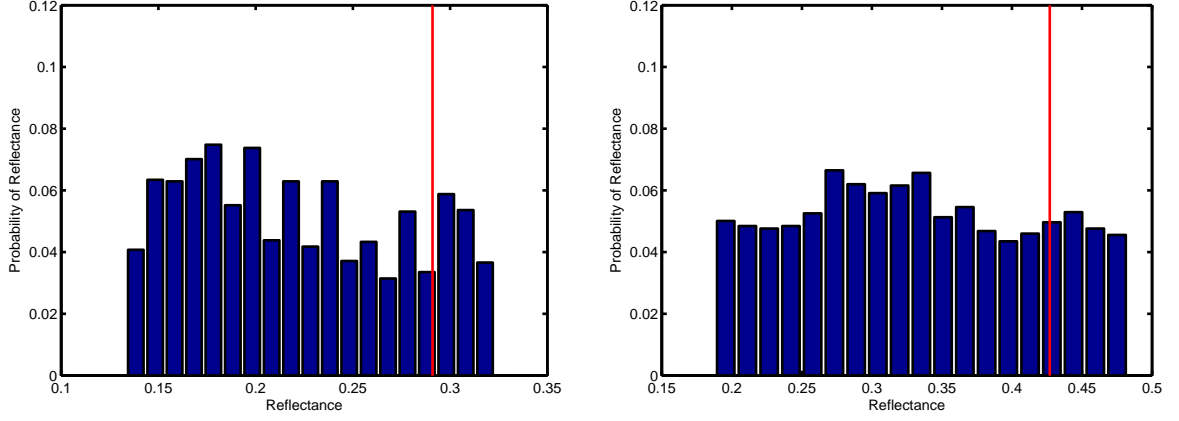
Figure 4.14:   (Left) Distribution of the Type I/II skin pixels for the green channel of the HST3 image. (Right) Distribution of the Type I/II skin pixels for the red channel of the HST3 image. The red line shows where the expected diffuse skin reflectance is located, per Table 4.2.
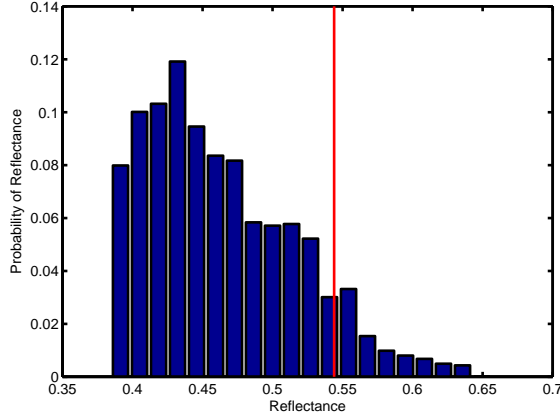
Figure 4.15:   (Left) Distribution of the Type I/II skin pixels for the melanin estimation channel of the HST3 image. The red line shows where the expected diffuse skin reflectance is located, per Table 4.2.

$$\mathrm{BC} = \sum_{i=1}^{n} \sqrt{p_i \cdot q_i} \tag{4.1}$$

where p_i and q_i are the fraction of PMFs p and q that fall within the ith bin and n is the number of bins. This results in a coefficient with a range of 0 (no overlap) to 1 (complete overlap) [28]. The BC computed between each pair of distributions of each of the different bands is shown in Fig. 4.17. The BC indicates that the distributions
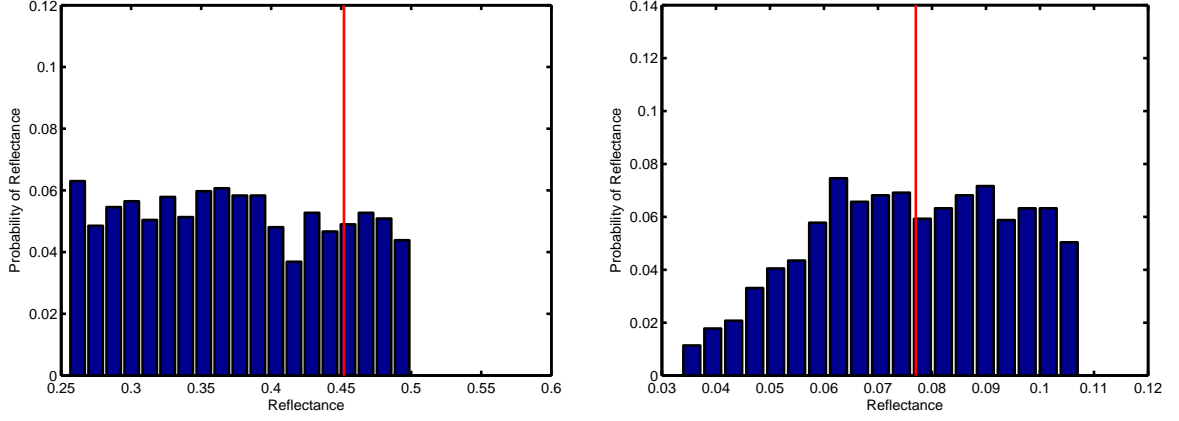
Figure 4.16:   (Left) Distribution of the Type I/II skin pixels for the filtered 1060nm channel of the HST3 image. (Right) Distribution of the Type I/II skin pixels for the filtered 1570nm channel of the HST3 image. The red line shows where the expected diffuse skin reflectance is located, per Table 4.2.
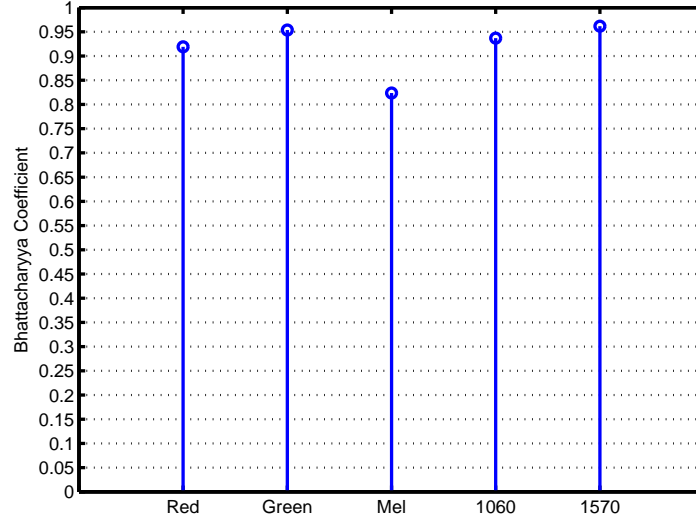
Figure 4.17:   The Bhattacharyya coefficient comparing each of the designed skin detection system distributions to the HST3 distributions. Red and green correspond to the color channels for *Camera 1*; Mel corresponds to *Camera 2*; 1060F and 1570F correspond to the use of the Semrock bandpass filters on *Camera 3* and *Camera 4*.

are highly overlapping which indicates a good correspondence between the system designed in thesis and the HST3 used for skin detection in [23] for similar targets.

4.2.1.5 Discussion. The histograms relative to the expected value of the skin reflectance of the target at each camera are reasonable. In some cases, the expected value corresponds well with the mode (*Camera 2* and *Camera 4*). In other cases, the expected value overestimates reflectance as indicated by the distributions being skewed to the left (*Camera 1* red and green channels and *Camera 3*). This observation is consistent with the HST3 data. The spread of values in each of the histograms is due to a number of factors including the effect of directional reflectance and camera noise at each individual pixel. This is the case for all channels of the system designed in the thesis as well as the HST3 imager. The bi-directional reflection distribution function (BRDF) is an important aspect of the skin's optical properties and most likely has the largest effect on the spread of the estimations. This observation is supported by the high similarity between the distributions of the system designed in this thesis compared to the HST3 as indicated by the high BC values. The impact of not fully understanding the BRDF phenomena may result in the loss of detections or an increase in false-alarms. A study needs to be accomplished on this topic.

4.2.2 Comparing Modeled and Measured Reflectance.

4.2.2.1 Radiometric Model. To compare the model and measured reflectance of human skin, the model is run with the same indoor setup (Fig. 3.25) and camera specifications (Table 4.1) as the camera system. The radiometric model calculates the number of electron forming photons that hit the focal plane array and the estimated reflectance of a single target pixel using the process discussed in Section 3.5.1.

First, the number of electron-generating photons for three targets are provided. These targets include skin, a white *Spectralon*® panel, and a gray *Spectralon*® panel. Figure 4.18 (Left) shows the theoretical number of electron generating photons for each target per Eqn. (3.5). Figure 4.18 (Right) shows that the white *Spectralon*® panel's reflectance (red) is higher than the other targets and skin's reflectance (green)
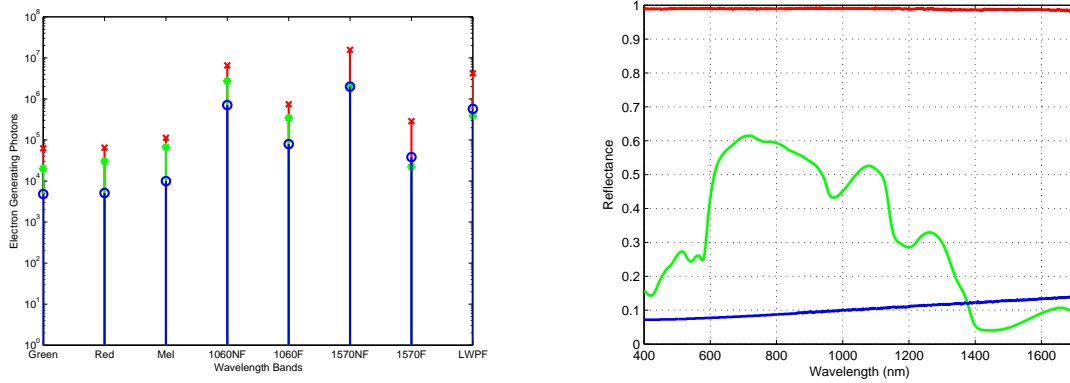
Figure 4.18: (Left) The number of electron-forming photons hitting the focal plane array of each camera with three different targets. The red × represents the white *Spectralon*® panel, green ∗ represents skin, and blue ○ represents the gray *Spectralon*® panel. The labels on the x axis of red and green correspond the color channels for *Camera 1*; Mel corresponds to *Camera 2*; 1060NF and 1570NF correspond to what *Camera 3* and *Camera 4* see with only their respective mirrors reflecting and transmitting; 1060F and 1570F correspond to the use of the Semrock bandpass filters on *Camera 3* and *Camera 4*. Lastly, LWPF corresponds to the use of the Reynard corporation longwave pass filter on *Camera 4*. (Right) The measured reflectance of each target shown in the model. Red corresponds to the white panel, green corresponds to skin, and blue corresponds to the gray panel reflectance.

is higher than the gray panel's (blue) out to 1370nm, where the gray panel's becomes larger than skin's. Qualitatively, the photon counts agree with what is expected due to the reflectance of each target. Furthermore, the system filter configurations that have large pass bands show a higher photon count as expected.

To compare the radiometric model to the skin reflectance values in Table 4.2, the photon count values need to be converted into reflectance using the empirical line method. This conversion can be done because photon count relates directly to the data numbers reported by the individual cameras. The P_{white} and P_{gray} values discussed in Eqn. (3.6) are the red × and blue ○ values shown in Fig. 4.18 (Left), respectively.

The results of estimating the skin reflectance using the empirical line method are shown in Fig. 4.19 as a red ○. Also shown on Fig. 4.19, as a blue ×, is the
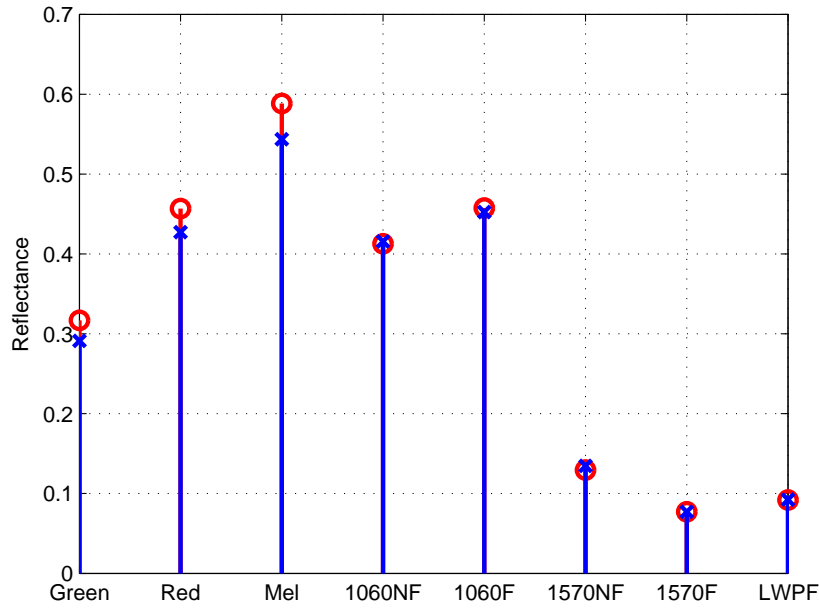
Figure 4.19: The estimated reflectance of skin found by using empirical line method represented as a red ○. Actual skin reflectance is represented by a blue ×. The labels on the x axis of red and green correspond the color channels for *Camera 1*; Mel corresponds to *Camera 2*; 1060NF and 1570NF correspond to what *Camera 3* and *Camera 4* see with only their respective mirrors reflecting and transmitting; 1060F and 1570F correspond to the use of the Semrock bandpass filters on *Camera 3* and *Camera 4*. Lastly, LWPF corresponds to the use of the Reynard corporation longwave pass filter on *Camera 4*.

actual measured reflectance value of skin used in the comparison [Fig. 4.18 (Right)]. Figure 4.20 shows the difference between the estimated and the actual reflectance of the target.

4.2.2.2 Discussion. These results show theoretically that any filtering choice for *Camera 3* and *Camera 4* provides the same result. With the values as close as they are, the logical choice would be to use no filtering because the amount of received energy is much higher, compensating for the relatively low solar illumination in the NIR seen in Fig. 2.5. However as seen in Fig. 3.33 (Red) and Fig. 3.34 (Red), the no-filter option integrates over a large band in which no study has been done to
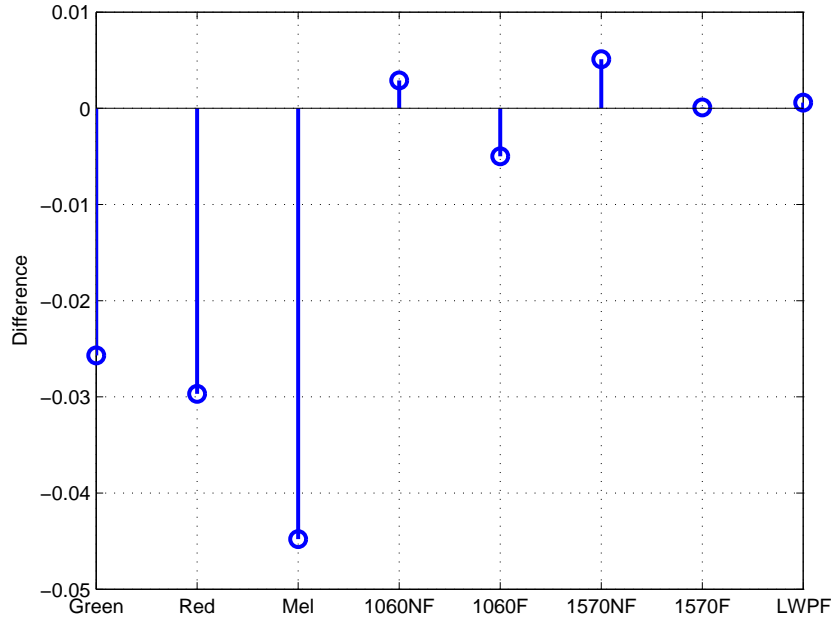
Figure 4.20:   The difference between the estimated and actual reflectance of measured skin shown in Fig. 4.19. A negative value means the estimated reflectance is higher than the actual reflectance. Red and green labels correspond the color channels for *Camera 1*; Mel corresponds to *Camera 2*; 1060NF and 1570NF correspond to *Camera 3* and *Camera 4* see with only their respective mirrors reflecting and transmitting; 1060F and 1570F correspond to the use of the Semrock bandpass filters on *Camera 3* and *Camera 4*. Lastly, LWPF corresponds to the use of the Reynard corporation longwave pass filter on *Camera 4*.

see how false detections are affected. Finally, the estimates for the NIR have less error than the VIS. The difference in error may be a result of a difference between the actual quantum efficiency of the camera and the quantum efficiencies used in the model.

4.2.3   Comparing the Physical System and the Theoretical Model.   The model and the physical camera system are compared based on their estimated reflectance from the target in Fig. 4.5. With regards to the physical system, the reflectance value chosen is the mode of the distributions shown in Fig. 4.8 (Left,Right), 4.10, and 4.11 (Left,Right). Figure 4.21 compares the reflectance of the physical system, model,

and the actual reflectance values of the skin in Fig. 4.7 (Left). The red and green show the widest variation. The system underestimates both channels, the red more significantly. The model appears to overestimate, but only slightly. This is likely because the model and the skin reflectance measurements do not contain a specular component where as the measurements by the system do. The values for 1060F and 1570F are close in all three cases. A small difference still exists and this is most likely do to BRDF properties that need to be studied. The reason that they are closer than the other bands is due to the small bandwidth the Semrock filters transmit. As shown in Fig. 4.19 the smaller bandwidths give better estimations of reflectance. The estimated reflectance for the melanin band shows that the model estimates the values higher than actual, but the physical system is very close to the actual value. The cause for the model estimates to be further away than the system estimates is unclear. The difference in error may be a result of the quality differences in the focal plane arrays, which could indicate the Goodrich cameras (NIR) have less noise than the ThorLabs cameras (VIS). Furthermore, this observation may support the statement that skin is more specular in the VIS than the NIR due to the high absorption of the longer wavelengths. Additional work is needed to better understand these issues.

4.3 Operational Analysis

The system's operational ability to detect skin and discard false-alarms is discussed and shown in the subsequent sections.

4.3.1 Basic Skin Detection.   The NDSI is calculated with the estimated reflectance resulting in Fig. 4.22 (Left). By setting the upper and lower thresholds for NDSI to 0.95 and 0.5 respectively, skin detection is accomplished and the snow as well as other objects are falsely detected. The detection using just NDSI is shown in Fig. 4.22 (Right).

4.3.2 False-Alarm Suppression.   To perform the NDGRI calculation, the reflectance of the red and green channels are estimated. The output of the NDGRI
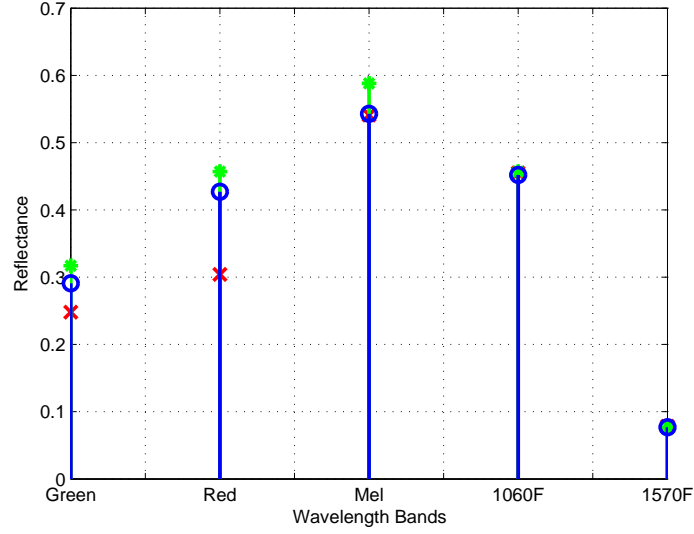
Figure 4.21:   Comparison of the model and physical system results. The red × represents the physical system's estimated reflectance, green ∗ represents the model's estimated reflectance, and blue ∘ represents the actual reflectance. Red and green correspond the color channels for *Camera 1*; Mel corresponds to *Camera 2*; 1060F and 1570F correspond to the use of the Semrock bandpass filters on *Camera 3* and *Camera 4*.
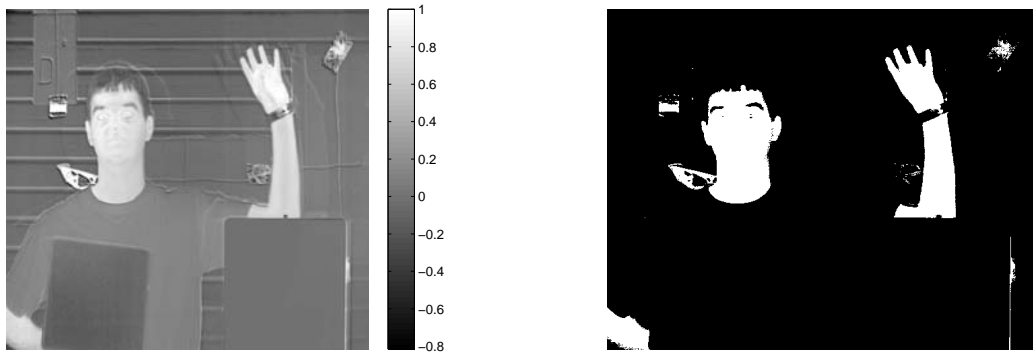
Figure 4.22:   (Left) NDSI calculated from the estimated reflectance of *Camera 3 and 4*. (Right) Skin detection using NDSI only accomplished by setting bounded threshold between 0.5 and 0.95.

calculation is shown in Fig. 4.23 (Left). The noise resulting from the high digital gain in *Camera 1* is apparent in the NDGRI image, especially around the target's hair and the left reflectance panel (gray *Spectralon*® panel). The pixels that fall within the threshold of -0.1 to -0.4 are shown in Fig. 4.23 (Right). Note that the snowball and

4-19
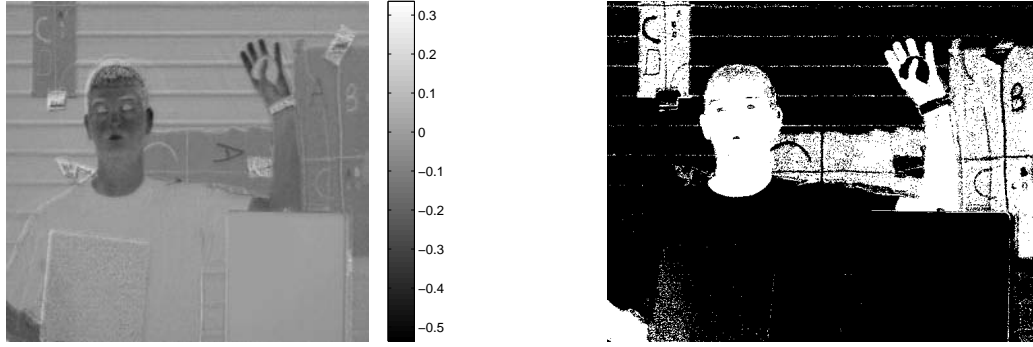
Figure 4.23:   (Left) NDGRI calculated from the estimated reflectance of the red and green channels of *Camera 1*. (Right) Pixels in the image meeting the bounded threshold between -0.1 and -0.4.

the other false-alarms shown in Fig. 4.22 (Right) are, for the most part, not included in the detection shown in Fig. 4.23 (Right).

4.3.3   Rule-Based Skin Detection.   Figures 4.22 (Right) and 4.23 (Right) are multiplied together to make the final detection mask shown in Fig. 4.24. The false detections in Fig. 4.24 occur for several reasons:

1. The target is not illuminated well enough and the noise dominated pixels result in the calculated values erroneously appearing within the threshold region. This issue is easily solved using a power threshold to ignore those pixels.

2. The cameras are not perfectly registered in both the x and y directions.

3. *Camera 1* does not exactly have the same FOV as *Cameras 3 and 4* due to the pixel size difference. This means that *Lens 2* may not be in the correct place.

4. Thresholds are not set correctly.

4.3.4   Melanin Estimation.   The melanin estimation element has a significant hardware issue. The drivers for the ThorLabs cameras do not allow for *Camera 1* and *Camera 2* to run at the same time in $MATLAB^{\circledR}$. As such, the melanin estimation implementation is not shown in the thesis. Based on the reflectance estimation of
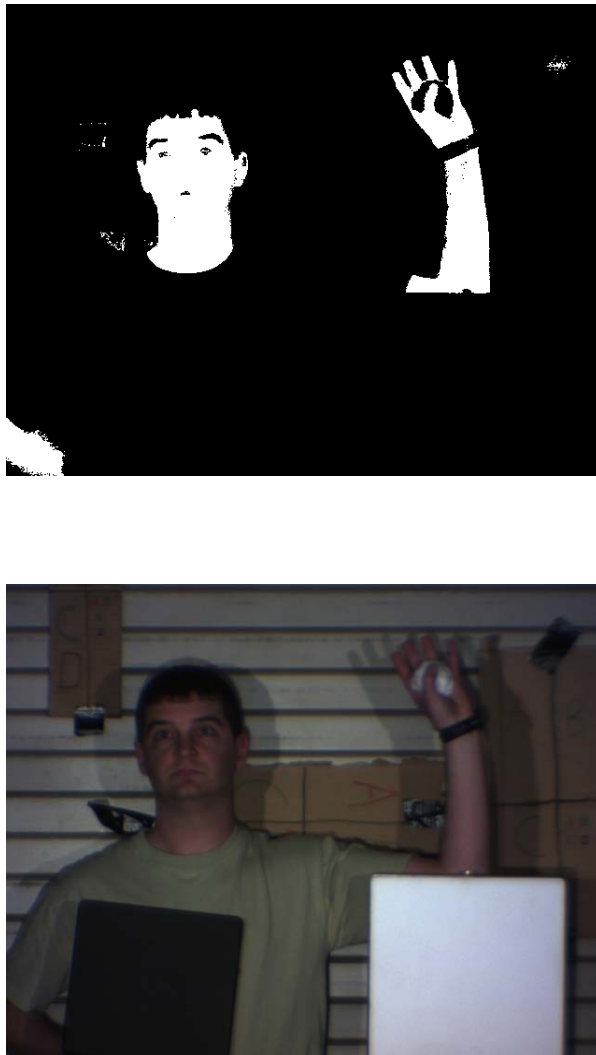
Figure 4.24:   (Top) Image of the final detection after the bounded NDSI and NDGRI
                detections are multiplied together. (Bottom) Color Image of scene to
                compare skin detection against.

Camera 2 analyzed in Section 4.2.1.2 and the operational results provided for skin
detection, it is anticipated that the melanin estimation will work as expected and
described in [23].

4.4   *Summary*

The skin detection, melanin estimation, and false-alarm suppression system is examined qualitatively, quantitatively, and operationally. Qualitatively, the image quality issues are resolved so that the images can be in focus at any target distance. Quantitatively, the model's photon estimations agree with what is expected. The estimated reflectance values from the camera system and the model compare favorably to the skin's measured reflectance. The distributions from the camera system are close to the same distributions generated by the HST3 used in the original work specified in [23]. This shows that two different imaging systems measuring under different illuminations have the effect in their distribution. This gives reason to further pursue topics such as BRDF. Operationally, skin detection and false-alarm suppression are done as described in [23], and results indicate the system designed in this thesis meets the intended use.

V. Conclusion

This chapter summarizes the accomplishments of this thesis and provides recommendations for future work. Finally, the contributions of this thesis work are discussed.

5.1 Summary

In this thesis, two main topics are discussed: designing and building a monocular multi-spectral skin detection, melanin estimation, and false-alarm suppression system [23] and designing a full radiometric model of that system. First, the operational scenarios for which this system is designed are low-altitude search missions, where real-time skin detection is its main use. As such, a system that can capture imagery at 1fps (with processing) and image at most 2in × 2in pixels from 710ft is required [25]. With these specifications in mind, the cameras, lenses, mirrors, and filters are selected. The camera selection is difficult due to a lack of visible cameras with 25μm pixels. However, the problem is addressed using a second lens for both visible cameras. The placement of each component makes it possible to use a single fore optic so registration problems due to depth of field are not an issue. Having a single fore optic makes it necessary for the incoming light to be divided appropriately (as specified in [23]) to each camera. Custom dichroic mirrors are specified and subsequently ordered to reflect and transmit the specific wavelengths to each camera with very high efficiency. The spectrum received by the near-infrared cameras used for skin detection are very broad so that different filtering bands can be experimented with in the future.

5.2 Possibility of Future Work

There are several interesting area of future work based on this thesis. Future work includes more advanced modeling, enhancements of the fore optic, enhancements to the hardware, and additional analysis under a broad range of operating scenarios.

The results of a bi-directional reflectance function (BRDF) study on human skin would be beneficial to better model the amount of energy that is incident on

the focal plane array resulting in a more accurate approximation of the what the imager encounters. Since much of the detector theory is based on a diffuse reflectance model [4,23] This might lead to a better understanding of the threshold values needed or may result in new detector components to take this information into consideration. Camera noise is another aspect that needs to be modeled. With the addition of camera noise, the true response of the cameras can be modeled.

The physical system should be run through an optical design program so that the highest quality images can be seen in all cameras. With such a program, a zoom lens can be added to the system to enhance its operational use. For example, if a few pixels are detected as skin, the camera can be zoomed into the area of interest for more detailed view. Another issue at hand is understanding why the ThorLabs camera drivers do not allow for both cameras to run at the same time in $MATLAB^{®}$. Further work should address stability issues with the laptop frame-grabber cards required for the Goodrich cameras. Moving to a laptop-based acquisition system increases system flexibility for use in different operational environments.

Now that the system is built and running as expected, additional controlled data collects need to be accomplished to determine how detecting and characterizing skin is affected by illumination differences. As the model is modified with BRDF and camera noise parameters, the model could be used to accomplish some of this analysis. Additional analysis can include a study on how pixel size affects detection. Finally, an in-depth study of the type of filters to use needs to be done to find what filter combination gives the best detection and false-alarm performance.

5.3   Concluding Remarks

In this thesis, a complete optical system and model are developed to aid in human skin detection. While skin detection is done presently, this system is the first of its kind using VIS and NIR wavelengths to detect skin, suppress false-alarms, and estimate melanin. These operations are done at frame rates of 10fps using engineering software, but the cameras used can support up to 30fps. The search and rescue

community will benefit from this system by increasing the likelihood of image analysts and ground teams finding lost persons. Not only search and rescue will benefit from this. Special operations and manhunter missions can use the technology developed here. Finally, the system developed provides a gateway to human measurements and signatures intelligence (H-MASINT), and when combined with human detection system such as that in [4], offers endless capability.

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14. ABSTRACT

A real-time skin detection, false-alarm reduction, and melanin estimation system is designed targeting search and rescue (SAR) with application to special operations for manhunting and human measurement and signatures intelligence. A mathematical model of the system is developed and used to determine how the physical system performs under illumination, target-to-sensor distance, and target-type scenarios. This aspect is important to the SAR community to gain an understanding of the deployability in different operating environments. A multi-spectral approach is developed and consists of two short-wave infrared cameras and two visible cameras. Through an optical chain of lenses, custom designed and fabricated dichroic mirrors, and filters, each camera receives the correct spectral information to perform skin detection, melanin estimation, and false-alarm suppression. To get accurate skin detections under several illumination conditions, the signal processing is accomplished in reflectance space, which is estimated from known reflectance objects in the scene. Model-generated output of imaged skin, when converted to estimated reflectance, indicates a good correspondence with skin reflectance. Furthermore, measured and modeled estimates of skin reflectance indicate a good correspondence with skin reflectance.

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